SLURRY REACTORS

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I. INTRODUCTION

The object of this report is two-fold: first, to summarize and analyze information pertaining to slurry reactors and second, to present the design of a possible future type of reactor designated the "Vapor Slurry Reactor".

During the existence of the Manhattan Project much work was done on design of homogeneous reactors using slurry fuels. Gradually the emphasis on slurries was dropped and the trend of thinking turned to fluid fuels. Today many engineers have eliminated the slurry reactor from consideration because of the large number of unknowns concerning slurries in comparison with fluid fuels. The need was seen for a report dealing specifically with the slurry reactor and its properties, advantages and disadvantages. Hence, a portion of this thesis is a summary of the previous work on slurries and slurry fuel reactors, and it is hoped that it will serve as a ready reference to those who are considering use of slurry fuels.

Many of the problems concerning slurries have not yet been answered so that this report is limited in scope and can only suggest possible solutions. The primary problems to be solved or investigated in the development of slurries are stability, erosion, corrosion, caking, heat transfer, handling, and effects of radiation. It is evident that each of these problems is dependent on the specific properties of the individual components of the slurry. The principal slurries which have been considered for use in nuclear reactors are uranium oxide in water, uranium oxide in hydroxides, thorium oxide in water, and intermetallic compounds in liquid metals.

Space and time limit a complete analysis or discussion of all the aspects of the problems pertaining to slurry fuels and thus, many references have been listed in the appendix as an aid to obtaining the complete picture.

The design of the Vapor Slurry Reactor was conceived during the work on slurry fuels and is presented in the latter part of the thesis. Preliminary thermal and criticality analyses of this reactor were completed. The detailed calculations involved in these analyses are presented in the appendix as possible aids for future, similar analyses. This design appeared to possess many advantages, possibly the most important of which was the capacity for production of high temperature steam. For example, the preliminary design that was completed for presentation in this thesis featured production of steam suitable for modern turbo-generators with throttle inlet pressures and temperatures of 1450 psig and 1000° F. The principal problems of the Vapor Slurry Reactor appear to be slurry erosion, the possible separation efficiency of cyclone separators, and the problems concerned with passing radioactive steam through turbines. None of these difficulties appear unsurmountable and thus, the design seems feasible. The Vapor Slurry Reactor illustrates some of the many possibilities yet unexplored in the use of slurry reactor fuels.

II. CHARACTERISTICS OF SLURRIES

Slurries have been used in the past for conveying grain, coal, cement, ash, soil, and sand, and there are numerous other applications chiefly in the chemical and mining industries. A wealth of data or theory describing the properties of slurries does not exist so that the design of a slurry system is somewhat of an art requiring years of experience or much preliminary experimental work.

Definitions are in order because of discrepancies which exist in terminology used to designate the suspension of a solid by a fluid. In this report the term "slurry" will define the suspension of any solid by any fluid. "Fluidized solid" is defined as a bed of solid particles through which a gas or vapor is flowing in such a way that the particles are maintained in suspension but are not transported. The "boiling bed" as used in the catalytic cracking of petroleum is an example of a fluidized solid bed. Suspensions of clay, sewage, grain, or pulverized coal are examples of slurries. The terms "entrainment", "suspensoid", and "dispersed suspension" have been used to designate the condition which exists when solid particles are fully suspended and transported by a gas stream. Classification has also been made under the head of "dispersoids" with "aerosol" defining suspension with gas and "hydrosol" defining suspension with liquid. The preceding definition of slurry includes and supersedes these terms for designation of solid suspensions.

The chief problems concerning a slurry which are important from the standpoint of reactor application are stability against settling and flocculation, caking, erosion and corrosion, radiation and fission effects, heat transfer, and slurry handling. The primary physical variables of a slurry which are available for controlling these characteristics are the density of the fluid and solid; the viscosity of the fluid; the size, shape, hardness, and surface properties of the solid particles; the concentration of the solid in the suspension; and the thermal properties of the solid and fluid. Relations between the characteristics and variables of a slurry will be discussed in the following paragraphs.

A. Mechanical Stability

The mechanical stability of a slurry refers to the preservation of the homogeneity of the suspension of the solid in the fluid. A suspension may become unstable by settling or by flocculation. When considering a slurry for a reactor, some means of maintaining an approximately homogenous suspension of the solid in the fluid is desirable in order to prevent changes in reactivity.

Homogenous slurry suspensions which are stable against settling may be maintained by one or combinations of the following methods:

1. Use of turbulence and eddies of the fluid medium. The drag or friction of the fluid on the solid particle promotes suspension. Turbulence may be achieved by pumping the fluid at a velocity such that the fluid imparts sufficient energy to the particles to annul the effect of gravity and maintain their suspension.

Forced agitation by stirring, vibrating or some other means is also available for achieving suspension with turbulence.

2. Use of fluid and solid slurry components with equal or matched densities, thus maintaining static equilibrium.
3. Use of extremely small particles which will not settle for long periods of time because of size. A colloid is an example of this type of suspension.
4. Use of stabilizing agents such as bentonite to prevent solid settling.

Much of the thought concerning development of slurries for reactor fuels has been along the lines that it was necessary to have a stable slurry which would not settle at any time. This type of slurry would involve suspension by one of the latter three of the above methods. It is to be emphasized that this concept may be true for a static slurry reactor in which the slurry is contained in one large pot, but is certainly not true for a cirulating or boiling slurry reactor in which the suspension may be maintained by turbulence.

Turbulence as a method of achieving stability against settling has the advantage of providing a positive mechanical means of suspension which is not dependent on the chemical and only partially dependent on the physical properties of the solid or fluid. This may be a decidedly important factor when considering reactor use of a slurry, since the properties of the slurry may constantly change due to the effects of radiation and fission. Turbulence is, of course, the chief means available for maintaining suspension of a solid in a gas. Possible disadvantages of using turbulence to maintain suspension are greater erosion of structural materials and greater attrition of the slurry.

Matching solid and fluid densities is an ideal means of promoting stability. The problem is to find the components with equal densities in conjunction with optimum physical, chemical, thermal, and nuclear properties.

Suspensions of fine particles are stable primarily because of the effect of Brownian movement. Brownian movement is the term used to designate the effect of the bombardment of the suspended solid particles by the molecules of the fluid. This effect is largely a function of particle diameter and becomes appreciable in comparison with gravity settling at particle diameters of about 3 microns. Brownian movement is the predominant effect on particle settling at particle diameters below 1 micron (1)*. A colloidal suspension is one in which the particle diameters range from 0.1 to 0.001 micron. Colloidal suspensions usually possess a higher viscosity than other types and may be undesirable from the standpoint of pumping power required. Tendencies to flocculate and cake and difficulties in separating the solid from the fluid may also make colloidal suspensions undesirable.

Stabilizing agents stabilize a suspension against settling in various ways, their effectiveness depending on the properties of the solid and fluid components. Experiments are usually required to determine the feasibility of a stabilizing agent for a given slurry.

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*Refers to list of references in Appendix D.

Bentonite is a colloidal alumino-silicate clay which has proven to be useful for stabilization of some slurries. It retards the tendency for a suspension to settle by increasing the viscosity of the medium. This is similar to the effect of increasing the concentration of a slurry which retards settling due to increased effective slurry viscosity. Slurries stabilized with bentonite have been used as oil-well drilling muds. Increased viscosity, possible decrease in chemical stability, and introduction to the slurry of additional neutron absorbing materials may make stabilizing agents undesirable.

Flocculation is an undesirable effect resulting from adherance of colliding slurry particles. Slurries consisting of variable size particles have greater tendencies to flocculate than those composed of equal size particles. Flocculation is undesirable because of the particle growth and the change in effective slurry viscosity which result.

Various additives are useful in preventing flocculation. The usual action is the imparting of either a negative or positive charge by absorption of the deflocculating agent on the surface of the particle. This results in particles with like charges being repelled (2). Phosphates are well known deflocculating agents for water systems (3). The effectiveness of sodium pyrophosphate, sodium chloride, sodium hydroxide, sodium oleate, calcium chloride, gum ghatti, and tannates as deflocculating agents for bentonite stabilized drilling muds has been studied by Kennedy (4).

Deflocculating agents may either increase or decrease the viscosity of the slurry. They may be undesirable because of increased neutron absorption and because of possible increases in the corrosiveness of the slurry.

Turbulence of the fluid may also be effective in deflocculating the solids.

Other possibilities exist for stabilization of slurries. The effect of a sound field on solid suspensions is of interest. It is possible to orient and suspend solids in a fluid medium with applied sonic fields (5,6). Ultrasonics have been shown to neutralize dilatantcy of sand suspensions (7) and sonic fields have proven to be useful for breaking up paint pigment agglomerates (8). The action of a sonic field might be classified under the heading of turbulence.

The effects of electrical currents and of electrical and magnetic fields on slurries have not been investigated but appear to present possibilities for certain slurries.

B. Caking

Caking is the effect which occurs when the solids adhere to the materials containing the slurry. Caking is very undesirable in circulating slurry-fuel-reactors in that deposition of fissionable slurry particles on the walls in the reactor could result in large increases in reactivity due to too great a concentration of fissionable material in the core.

Additives which are effective in deflocculating a slurry may also retard caking. Turbulence of the fluid and use of ultrasonics are excellent possibilities for preventing caking.

C. Erosion and Corrosion

The properties of slurries prevent separation of the phenomena of erosion and corrosion. Many materials protect themselves from corrosion by forming an oxide coating on their surface. The slurry may wear away this coating and expose the base material to corrosion by the fluid. The slurry also may act to erode the structural material by particle impingement alone. Erosion or attrition of the solid particles themselves also may occur.

The principal factor determining the erosive tendency of a slurry is the hardness of the solid particles in relation to the hardness of the containing structural material. When considering a structural material for containing a slurry, one must also take into account the hardness or toughness of the oxide coat which the material forms. The speed with which the oxide coat of the material is replaced in a given fluid medium must also be considered.

Other important factors are velocity of the slurry relative to the structural material, particle size and concentration of the solids, and density of the solid relative to the fluid. An increase in velocity or particle size results in an increase in erosion. The effect of particle size on erosion has not been definitely established for particles below 100 microns in diameter. An increase in concentration of the solids usually results in an increase in the erosiveness of the slurry because of increased particle impingement. The greater the difference in density between the solid and the fluid the greater the erosiveness. This is especially true for slurries flowing in horizontal and curved tubes. When a slurry composed of particles which have a greater density than that of the fluid flows around the bend in a tube, the solids are thrown to the outside resulting in an appreciable increase in erosion.

Erosion of the particles and subsequent flocculation of the fines is an undesirable effect which may occur during the flow of a slurry.

D. Radiation and Fission Effects

It is evident that the study of radiation and fission damage to a slurry requires experimental in-pile tests and depends on the properties of the specific constituents of the slurry.

Fission in the solid particles of a slurry may result in the particles being broken up due to the fission forces. An increase in slurry viscosity is an undesirable result of this effect. A certain particle size may be ideal from the standpoint of resisting fission damage.

Production of various fission fragments may introduce new chemical activity to the slurry and cause corrosion, caking, or instability. The particle size of the solids is important in determining the percentage of the fission products which will escape from the slurry particle. A small particle size is desirable in order to allow for release of high cross section fission products such as xenon gas which subsequently can be removed from the fluid. If the particle diameter is made approximately equal to the average range of fission fragments in the solid, release of a large per cent of the fission products to the fluid will be assured.

E. Heat Transfer

Because of the intimate contact between the solid particles and the fluid, the heat transfer from a slurry particle within which heat is being produced is extremely rapid and efficient. For slurry particles of comparatively small size the temperature gradients across the particle and between the particle and the fluid stream are insignificant.

The heat transfer from a slurry flowing in pipes is of interest in that the slurry may be used as an agent for carrying the heat from the reactor core to heat exchangers. Orr (9) has shown that the heat transfer coefficient for a liquid-solid suspension flowing turbulently in a vertical pipe may be calculated from the Sieder and Tate relation

$$\frac{h_c D}{k_m} = 0.027\left(\frac{D v_m \rho_m}{\mu_m}\right)^{0.8}\left(\frac{c_{pm}\,\mu_m}{k_m}\right)^{1/3}\left(\frac{\mu}{\mu_w}\right)^{0.14} \qquad (1)$$

where the thermal conductivity and viscosity are evaluated by the equations below, the heat capacity is calculated as a weighted average of the values for the individual components, μ is the liquid viscosity at the bulk mean temperature, μ_w is the liquid viscosity at the temperature of the inner surface of the pipe wall, and the other notations are given by Appendix A. The viscosity of the slurry may be calculated with accuracy sufficient for heat transfer purposes by the equation

$$\mu_m = \frac{\mu}{\left(1 - \frac{e_v}{e_{vo}}\right)^{1.8}} \qquad (2)$$

where e_{vb} is the volume concentration of the solid in a bed resulting from gravity sedimentation of the slurry.

The thermal conductivity of the suspension is calculated by the Tareef relation

$$k_m = k\left[\frac{2k + k_s - 2e_v(k - k_s)}{2k + k_s + e_v(k - k_s)}\right] \tag{3}$$

Slurries composed of attapulgus clay, powdered copper, glass beads, powdered graphite, and powdered aluminum in water and of powdered graphite and powdered aluminum in ethylene glycol were used in confirming the above relations.

Little or no data exist for predicting heat transfer from gaseous slurries, however a relation developed by Mickley and Trilling (10) for external heating of dilute fluidized solids may provide an adequate approximation. For 1 and 4 in. diameter beds of glass particles fluidized with air, with solid volume concentrations from 1.6 to 50 per cent and superficial air velocities from 0.8 to 15 fps, the relation was found to be

$$h_c = 0.0118\left(\frac{\rho_c G_o}{d^3}\right)^{0.263} \tag{4}$$

where ρ_c equals the solid concentration in the mixture, lb per ft^3 and

G_o equals the superficial mass velocity based on total cross section without particles, lb per hr-ft^2 of cross section.

Better results might be obtained by use of the well known Dittus-Boelter relation in conjunction with the Hatschek relation (11, pp. 219, 223) for determining the viscosity and the Tareef relation (Eq. 3) for determining the thermal conductivity. The Hatschek relation is:

$$\mu_m = \frac{\mu}{1 - e_v^{1/3}} \qquad (5)$$

The Dittus-Boelter relation with the properties of the fluid replaced by the properties of the mixture is as follows:

$$\frac{h_{c,m} D}{k_m} = 0.023 \left(\frac{D v_m \rho_m}{\mu_m} \right)^{0.8} \left(\frac{c_{pm} \mu_m}{k_m} \right)^{0.4} \qquad (6)$$

where all properties are evaluated at the bulk temperature.

Heat transfer from fluidized beds may be of importance because of the possibility of using the slurry to carry the solids to a fluidized bed heat exchanger outside the reactor. McAdams (11) summarizes the results of various heat transfer studies on fluidized systems.

A method of flow visualization by use of phosphorescent particles suspended in a fluid (12) may prove valuable in determining the heat transfer properties of slurries.

F. Slurry Handling

One phase of slurry handling entails design of the system required to circulate the slurry. In order to facilitate this design, the pressure losses to be encountered in the flow of the slurry and the solid concentrations which can be carried by the slurry must be predicted.

Slurries may be classified as Newtonian or non-Newtonian suspensions. A Newtonian suspension is characterized by a viscosity which is independent of the rate of shear. Non-Newtonian suspensions are divided into five types: Bingham plastic, dilatant, thixotropic, rheopetic, and pseudoplastic. Each of these types are characterized by the relation of their viscosities to the rate of shear. Classification of the slurry into one of the above types is of interest in evaluating the viscous flow properties of the slurry. Lapple (1) is an excellent reference on the viscous flow of non-Newtonian suspensions.

1. Pressure Loss

Prediction of the flow properties of slurries flowing turbulently in tubes is a perplexing task. A definite relation for the pressure drop of a slurry which is accurate for all particle sizes, concentrations, temperatures, and slurry components has not yet been determined—possibly because of the many variables involved.

Caldwell and Babbitt (13) in their tests on clay and sewage suspensions found that the usual friction factor plots can be used provided the density of the mixture and the viscosity of the fluid are used in the Reynolds number. Because of its relative simplicty, this method of predicting pressure loss has been used by many investigators. However, data on slurries flowing at high velocities indicate that this method gives pressure losses which are much too conservative.

Various investigators have developed theoretical and empirical relations for predicting the pressure loss of slurries (14-19). It should be pointed out that many of these results do not agree or are in error due to the fact that all data were taken at one temperature or that the pressure measurements were made while the solid components of the slurry were still being accelerated to the carrying velocity.

An increase in the temperature of a slurry decreases the viscosity of the fluid and thus, additional turbulent energy is needed to maintain the suspension. This effect may not be accounted for by the change in Reynolds number and therefore, before writing a representative equation for the pressure loss of a slurry one must be sure that it is independent of temperature. The viscosity of a gas does not change as rapidly with temperature as does that of a liquid so that the deviation would not be as appreciable for gases.

In many investigations of vertical transport of solids by gases the acceleration of the solids from the point of injection into the gas stream was not allowed for. This resulted in predicted friction pressure drops that were too high.

Work at Iowa State College (20) on suspensions of spherical particles (0.0114 to 0.0505 in. dia.) of glass, lead, and steel in water flowing in horizontal tubes has indicated that the pressure loss of the slurry approaches that of the pure liquid as the velocity increases.

Recent investigation (21) has indicated that the head loss of a slurry may be expressed by the equation:

$$\frac{H_m}{L} = \frac{f}{2z}\left(\frac{v_m^2}{Dg}\right) \qquad (7)$$

where f is the friction factor from the standard Reynolds number correlation using the Reynolds number, $\rho D v_m / \mu$, and z is the reciprocal of the ratio of the pressure drop of the slurry to the pressure drop obtained for pure water flowing at the same velocity.

Dimensional analysis indicates that the variables, upon which friction loss of a slurry flowing turbulently in a tube depends, can be combined into the following nine dimensionless groups:

$$\frac{\Delta P}{\rho v_m^2} = \phi\left[\frac{L}{D}, \frac{\rho v_m D}{\mu}, r, \frac{\rho_s}{\rho}, \frac{d}{D}, e_s, \frac{v_m^2}{Dg}, \alpha\right] \qquad (8)$$

After it is recognized that the head loss of a pure fluid is a function of the first four variables, z can be expressed as a function of the last five variables:

$$z = \phi\left[\frac{\rho_s}{\rho_f}, \frac{d}{D}, e_s, \frac{v_m^2}{Dg}, \alpha\right] \qquad (9)$$

Plots of log z versus log (v_m^2/Dge_s) for a given material and particle size have proven to be independent of slurry temperature and volume concentration for temperatures from 59 to 122° F and for volume concentrations up to 16 per cent.

The following empirical relation was derived for z:

$$z = 1 - 7.89\left[\frac{v_m^2}{Dg}\left(\frac{1}{e_s}\right)\left(\frac{\rho}{\rho_s}\right)^{1/3}\right]^{-0.775} \qquad (10)$$

This equation held for all materials tested when $(v_m^2/Dg)\ (1/e_s)\ (\rho/\rho_s)^{1/3}$ was greater than 50. It can be seen that z is independent of d/D for this range. It is important that the head loss of the fluid and the slurry be expressed in the same units when using z (ft of mixture or ft of fluid). This relation was tested for 0.3 and 0.5 in. diameter glass tubes, for d/D ratios from 0.0373 to 0.230, and for ρ/ρ_s ratios from 2.53 to 11.3. The slurries tested showed Bingham plastic tendencies and Equation 10 may not hold for other types of suspensions.

Prediction of the flow properties of slurries may be further complicated by the fact that the fluid and solid components may not travel at the same velocity. Investigations at Iowa State College of aqueous slurries flowing in tubes have indicated that the average velocity of the solid approaches and may surpass the average velocity of the fluid at high slurry velocities. The velocity distribution of solid particles in a slurry flowing in a tube may be such that a greater concentration of particles travels through the center of the tube. This provides a possible explanation of how the average velocity of the particles can exceed the average velocity of the fluid.

2. Concentration

For obvious reasons the maximum concentration of solid particles which can be carried by a slurry reactor fuel is of importance.

Volume concentration is a more illustrative parameter than weight concentration for expressing the percentage of solids in a slurry, because weight concentration depends on the densities of the solid and fluid components. The maximum volume concentration which can be carried by a slurry is limited by the condition at which the slurry ceases to be fluid or by the condition at which the effective viscosity of the slurry becomes too great to allow pumping. Various investigations have indicated that this limiting volume concentration is approximately 44 per cent for aqueous systems with particles above 50 microns in diameter (22).

The size, shape, and surface properties of the solid particles affect the limiting concentration. For liquid slurries the solid particles must be wetted by the fluid in order for the suspension to be established. The maximum limiting concentration of the slurry decreases with a decrease in particle size. As the particle size approaches the range in which the effect of Brownian movement is appreciable, the limiting concentration decreases at a more rapid rate. Slurries of spherical particles have higher limiting concentration than those of odd shaped particles (22). The velocity with which the slurry is circulated also affects the concentration which can be carried.

Many schemes exist for determining slurry particle size. Dalla Valle (23) and Lapple (1) discuss details of the various methods.

Little appears in the literature on the maximum concentration which can be carried by a gaseous slurry. The work of Cramp (15) on conveyance of grain indicates that the limiting volume concentration is about 2.5 per cent. The maximum concentration increases directly as the square of the gas velocity (24) and also depends on the density of the solid particles in relation to the density of the gas and on the particle size and shape. The relation between particle size and limiting concentration, which exists for liquid slurries, may not be apparent for gaseous slurries.

It is desirable to measure the concentration of reactor slurries during flow without taking samples of the slurry. Several possible schemes for such measurement are as follows:

1. Measurement of difference between the pressure drop in a vertial or inclined pipe and that in a horizontal pipe(25,26).
2. Measurement of scattering or attenuation of gamma rays directed on or through the pipe containing the slurry (25,27).
3. Measurement of weight of a flexibly coupled pipe carrying the slurry (28).
4. Measurement of the product of density and viscosity by measuring the power required to maintain reciprocation of a probe immersed in the slurry (Ultra-Viscoson marketed by Bendix Aviation Corp.) (25).
5. Measurement of difference in pressure differentials of flow through two pressure differential creating devices, one of which carries the slurry and the other of which carries the pure fluid (29).

3. Pumping and Separating

Liquid slurries may be transported by centrifugal, electromagnetic, or gas lift pumps. The electromagnetic (EM) pump is ideal from the standpoint of not requiring sealing or moving parts, but requires a slurry that is a good conductor. The EM Pump has a smaller capacity than the centrifugal pump.

Recently the "gas lift" pump was proposed for handling reactor slurries (30). Although this type pump has low capacity, its advantages from the standpoint of sealing and erosion make it very feasible for pumping slurries. Gas lifts have been evaluated in connection with operation of oil wells (1).

The chief problems in designing centrifugal pumps for reactor slurries are sealing the pump to prevent escape of highly radioactive slurry, erosion of the moving parts in the pump, and protecting the pump bearings from the slurry. Canned rotor pumps appear to be the most suitable centrifugal pump for handling slurries and solve the sealing problem. Systems for forcing fresh fluid through the pump bearings may prevent the slurry particles from reaching the bearings. Erosion of high speed pump impellers by a slurry composed of hard particles is a critical problem, the solution of which depends on development of harder more durable impeller materials. Systems involving separation of the slurry before the pump and subsequent remixing in a high velocity jet ejector following the pump present possibilities for pumping erosive slurries. This possibility does not appear to have been investigated and is illustrated by Figure 1.

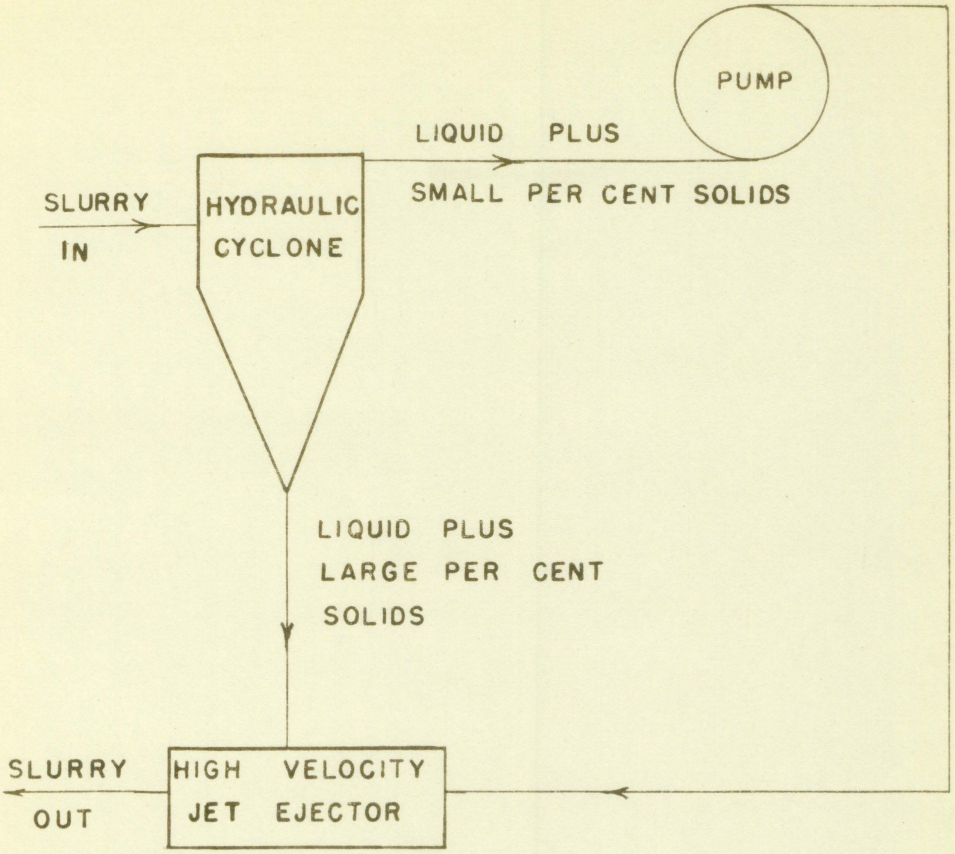

FIGURE 1. POSSIBLE SCHEME FOR ELIMINATING PUMP EROSION BY LIQUID SLURRIES.

Jet pumps and gas lift pumps are probably the most feasible method of pumping gaseous slurries.

Methods of separating the solid particles from the fluid may be of importance in processing slurry fuels or in certain types of slurry reactor designs (see proposed design of Vapor Slurry Reactor). A feasible mode of solid separation for reactor slurries appears to be use of centrifugal separators. Centrifugal separators which remove solids from a gas are referred to as cyclone separators while those which separate solids from a liquid are called hydro-cyclones or hydraulic cyclones.

Cyclone separators have been used many years for dust collectors and ash removers. The separation efficiency is dependent on particle size, solid concentration, inlet velocity, and size of the cyclone. It increases with an increase in particle size, concentration, or velocity and a decrease in cyclone diameter. The pressure loss through the cyclone also increases with an increase in velocity or decrease in cyclone diameter. For conventional industrial cyclones it has been reported that the loss is 4 times the inlet velocity head (31, P. 811). Cyclones may be used in parallel arrangement to get high separation efficiencies in conjunction with high flow rates. Collection efficiencies of 98 per cent have been achieved for separation of heavy concentrations of dust down to 2 microns in diameter. Cyclone separators have been designed to operate at temperatures up to 1000° F (1,23,32).

Hydraulic cyclones have been used in industry for desliming coal. The variables affecting their operation are much the same as for cyclone separators. Separation efficiences of 90 per cent with particles down to 30 microns in diameter are achievable (33,34). A 10 mm diameter cyclone that will separate 2 micron clay particles from water has been reported (35).

Oak Ridge National Laboratory has started development of hydraulic cyclones to remove precipitated PuO_2 from blankets and insoluble fission products from reactor fuels (35,36).

III. PROGRESS IN THE DEVELOPMENT OF REACTOR SLURRIES

After reading the previous discussion of the properties and difficulties of slurries, one might ask the question—why use a slurry for a reactor fuel when a fluid is so much easier to handle? There are several reasons why slurries have been considered for nuclear reactor fuels:

1. Fluids which will combine with fissionable or fertile material (U, Th, Pu) sometimes are so corrosive that no structural materials can be found that will contain them for long periods of time at temperatures desirable for reactor operation.
2. Desirable concentrations of fissionable or fertile material sometimes cannot be incorporated in fluids which have ideal heat transfer, physical, or nuclear properties and chemical, thermal, and radiation stability. Slurries can be prepared in heavy or light concentrations of fissionable or fertile material while this is not always the case with fluids. Slurries may incorporate fluids such as heavy water which have ideal nuclear porperties. A non-corrosive fluid with suitable nuclear properties has not been found that will combine with thorium in concentrations suitable for breeding applications.

Most of the work on reactor slurries has centered around the use of four fluids—aqueous solutions, hydroxides, liquid metals, and gases. Extensive work has been done on the Manhattan Project (22,37,38), at Oak Ridge National Laboratory (ORNL) (3,25,35,36,39-50), and in the Netherlands (30) on development of slurries of the oxides of uranium in aqueous solutions.

ORNL has also developed thorium oxide-aqueous slurries. Brookhaven National Laboratory (52,53) has developed slurries consisting of intermetallic compound suspensions of U and Th in liquid metals. Various work has been done on slurries utilizing hydroxides as the fluid element, chiefly in conjunction with work on development of a reactor suitable for aircraft propulsion (56-64). Some work has been done on gaseous reactor slurries, however most of this has been in conjunction with development of fluidized solid beds (30,65,66). The following discussion is a brief summary of the investigations on each of the reactor slurries.

A. Uranium Oxide-Aqueous

An excellent summary of the early Manhattan Project investigation of uranium oxide slurries is presented by Kirshenbaum (22). This work consisted chiefly of investigation of the chemical, thermal, and physical properties of the oxides, although some erosion and corrosion work was done for specific structural materials. Uranium dioxide (UO_2) and black oxide (U_3O_8) were reported to have scratch hardnesses of Moh 3.5 depending on their previous history, and hydrates of uranium trioxide (UO_3) were reported to have a scratch hardness of Moh 2.5.

Early work at ORNL was devoted to development of aqueous uranium oxide slurries that would not settle under static conditions. Because of many difficulties involved with the use of stabilizing agents this work was dropped in favor of development of slurries which could be easily redispersed after settling. ORNL specified that a slurry containing 200 gm of oxide per liter which was stable against caking and flocculation at 482° F (250° C) and 1000 psia would be suitable for the reactor application which they had in mind. Investigation showed that UO_3 was the stable equilibrium form of the oxide for aqueous slurries at 482°F (43) and consequently most development centered about UO_3 slurries.

The chief problems which arose in the development of UO_3-aqueous slurries were those of flocculation and caking. Additives consisting of phosphates proved successful for preventing flocculation. Caking was prevalent in many of the pumping tests which were run on UO_3-H_2O slurries in 347 stainless tubing and several possibilities were investigated in an effort to correct this. Slurries containing 150 gm of oxide per liter as 1 part of uranium oxide monohydate (UO_3-H_2O) and 2 parts of uranyl phosphate $[(UO_3)_3(PO_4)_2 \cdot H_2O]$ were circulated for 480 hr. with little evidence of caking (48). The addition of the phosphate increased the corrosiveness of the slurry but this did not appear to be critical. The phosphate also increased the viscosity of the slurry, resulting in requirements for greater pumping power.

Experiments at ORNL have proven the erosion by UO_3-H_2O slurries to be uncritical for use in stainless steel.

Pumping tests of slurries were successful with Westinghouse 200A canned rotor pumps. Some difficulty resulted from the slurry reaching pump bearings, however the chief problem was particle degradation by high speed pump impellors.

Various tests were made to determine the relation of the viscosity of uranium trioxide slurries to temperature and solid concentration.

Radiation effects on UO_3-H_2O were studied and the results were favorable. A 93 per cent enriched uranium trioxide slurry was irradiated for four weeks at a neutron flux of $7x10^{11}$ neutrons per sq cm per sec. Considerable degradation of particles to fines and fragments occured. Caking of the slurry on the interior surfaces of the radiation bomb was also prevalent (3). A natural uranium oxide slurry was exposed to a fission density of 0.2 watts per gm. of uranium oxide and its properties were essentially unimpaired. Little caking or particle degradation occured (46). The latter test indicated partial reduction of the uranium oxide; however a similar effect was not apparent after the irradiation of the enriched slurry.

Studies were made on the effects of traces of fission products on corrosion by uranium trioxide slurries and it was concluded that fission products would not appreciably increase the corrosiveness (46).

Magnesium-uranate ($MgO \cdot UO_3$) and urynal carbonate (UO_2CO_3) were investigated as possible alternate slurries. Magnesium uranate slurries were unsuitable because of their tendency to cake (42) and uranyl carbonate slurries decomposed at 482° F (47).

The Reactor Development Group of the Netherlands Reactor Committee (NRC) has designed two reactors utilizing oxides of uranium (30). Uranium dioxide was selected as the most favorable oxide. It was found that UO_2 is thermally stable at 482° F which is contrary to the findings of ORNL. Mention was made of the fact that the surfaces of all the oxides consist of UO_3 in a hydrated form and this may account for the different results. The NRC found that UO_2 suspensions did not flocculate or cake when the pH of the slurry was between 7 and 10. A value of Moh 4 was determined for the scratch hardness of uranium dioxide and erosion of the slurry but not of the structural materias was expected. The effect of radiation and fission damage was investigated in Jeep at a flux of $8x10^{11}$ neutrons per sq cm per sec. and the stability remained. The NRC proposed use of gas lift pumps to move the slurry, and thus eliminate sealing and bearing difficulties. and high velocity contact.

Slurries of U_2O_5 have been prepared and show promise (51).

B. Thorium Oxide-Aqueous

Because of inability to combine thorium with fluids suitable for reactor use, ORNL has done extensive work on development of thorium dioxide (ThO_2) slurries for use in breeder blankets. Slurries were prepared in concentrations up to 1000 gm per liter which were easily redispersed after settling.

The errosiveness of thorium dioxide slurries was the primary problem. Slurries prepared by calcination of thorium oxalate have exibited a hardness of Moh 7.5 (3) while the hardness of 347 stainless steel is Moh 6 to 6.5. The hardness of thorium oxides proved to be a function of the method of preparation and oxides prepared from thorium hydroxide were less erosive (47).

Pumping tests in stainless steel tubes on slurries composed of the harder form of ThO_2 indicated that erosion was not serious at velocities below 20 fps in linear sections. Drastic erosion of the tubes occured at

90 fps. Erosion of pump impellors, flow restrictors, and tube bends was serious at all velocities (35).

Additions of O_2 and PO_4 ions to the ThO_2 slurries were found to reduce the attack on stainless steel. Titanium proved to be a more erosion resistant material although its hardness is not greater than that of stainless steel. This was though to be due to the fact that titanium formed a stronger oxide film or that its oxide film was more rapidly replaced after abrasion. Three materials were found that will stand up under abrasion by ThO_2—hard chrome plate on steel, stellite, and oxidized zirconium (47). ORNL concluded that relative crystallinity and past history of the thorium dioxide were more important effects on errosiveness than particle size (48).

Marked increases in viscosity and decreases in settled bulk density were observed in an extended pumping test. These effects were found to be the result of attrition of the slurry particles followed by flocculation of the fines (36). Sodium silicate, calgon, and sodium pyrophosphate proved successful as deflocculating agents. Oxalic acid and malonic acid proved to be effective in reducing the viscosity (49).

ORNL prepared mixed slurries of UO_3 as a solid solution in ThO_2 which were stable at 482° F. This slurry was not as abrasive as ThO_2 and presented possibilities for use as a combined fuel-breeder.

ThO_2 slurries are reported to be stable against radiation (50).

C. Intermetallic Compound-Liquid Metal

Liquid metals are of interest in power reactor design because of their excellent heat transfer properties and adaptability to high temperature power cycles. A liquid reactor fuel utilizing the properties of liquid metals is extremely desirable.

Brookhaven National Laboratory (BNL) has designed liquid metal fuel reactors utilizing bismuth as the chief component of the fuel (52). The solubility of uranium in bismuth is only 3 per cent by weight at 1292° F (700° C) and thus, in order to obtain higher concentrations and reduce enrichment requirements, slurries were resorted to.

BNL developed various intermetallic compound dispersions which permitted higher fissionable or fertile material concentrations. Liquid metal slurries are ideally suited for stabilization by matching the density of the fluid with that of the solid and much of the work proceeded toward this goal.

Attempts to suspend the oxides of uranium in various liquid metals met with failure, because the oxides were not wetted by the liquid metal. Dispersions of U_3Bi_5 in Bi or Pb-Bi alloys were prepared. The density of this suspension was greater than that of the liquid thus giving some settling. Suspension of UBi in Bi-Pb alloys with 80-98 per cent Pb were found to be stable at 1112° F (600° C). This suspension allowed greater concentrations of uranium than U_3Bi_5.

The most promising suspension developed at BNL was an intermetallic compound of USn_3 which was stable in many Bi-Pb-Sn alloys. The density of USn_3 (10 gm per cm^3) was matched by alloys containing 3-5 per cent Sn, 35-40 per cent Bi and the rest Pb. Thus, this slurry is ideal from the standpoint of settling stability. Freezing points down to 203° F (95° C) were found to be possible for the liquid metal. The hardness of the USn_3 was approximately that of iron and the size and shape of the particles depended on the method of preparation.

Suspensions of Th_3Bi_5 in Bi and Bi-Pb alloys were prepared. The density of the solid was approximately equal to that of the fluid and this system appeared very feasible for breeding blanket applications.

Slurries of $PuSn_3$ and $PuPb_3$ in liquid metals, U in Ce, U in Cd, and U in Ca have been suggested as other possibilities (54). Lithium apparently does not alloy satisfactorily with uranium (54,55) and therefore, suspensions of metals or intermetallic compounds in Li^7 might possess many advantages for reactor application.

The concentrations achievable in these slurries were found to be limited by viscosity considerations. As discussed previously, the viscosity depends on the particle size and shape, and the volume per cent solids. A volume concentration of 25 per cent was assumed to be the maximum for the above slurries.

Mass transfer and plugging caused by thermal gradients seem to be the chief problems in the development of these fuels. Type 347 stainless steel was found to be the most suitable container material if used with corrosion inhibitors. Graphite is not attacked by Bi so that if used as moderator, it needs no cladding.

The heat transfer properties of these slurries will undoubtedly be comparible to those of liquid metals when proper allowances are made for the effect of the solids on the constants.

Liquid metals are not significally damaged by radiation and therefore, these fuels should also be stable.

D. Uranium Oxide-Hydroxide

Hydroxides have been considered as possible reactor fuels because of their excellent moderation properties, low neutron absorption cross sections, and low vapor pressures at high temperatures. Their light weight also presents advantages, if considering a reactor for aircraft or rocket propulsion. Attempts to combine uranium compounds with sodium hydroxide have met with little success (61,63) and thus, one must resort to the slurry in order to achieve suitable concentrations.

Uranium trioxide appears to be the most stable solid for use in NaOH slurries. $NaOH-UO_3$ slurries containing 5 per cent uranium by weight have been circulated in small flow loops at Battelle Memorial Institute (BMI). Considerable particle growth was apparent (56,59). These slurries were not stable against settling but were easily resuspended after standing for several days and no caking was apparent (63).

The chief problem with hydroxides was that of corrosion. Nickel, gold, silver, and platinum were the only metals which seemed to have any sort of corrosion resistance to the hydroxides (57,58,60). Nickel appears to be the more feasible for reactor use. Mass transfer, not intergranular corrosion, is the result of the attack on nickel by NaOH. It has recently been reported that additions of powdered aluminum or chromium to NaOH resulted in reduction and possible elimination of mass transfer up to 1500° F (62). This finding seems very favorable to the future development of hydroxide-slurry fuels. The properties of hydroxide slurries cannot be fully evaluated until mass transfer has been stopped.

The heat transfer properties of sodium hydroxide are good and undoubtedly are similar to those of the other hydroxides. It was found that for turbulent, forced convection of sodium hydroxide the following equation applies (64): $Nu = 0.021\, Re^{0.8}\, Pr^{0.4}$

This relation is similar to the Dittis-Boelter equation (Eq. 6) and thus, the heat transfer properties of sodium hydroxide are similar to those of most fluids.

Sodium hydroxide has proven to be very stable to radiation damage (61,63).

IV. SLURRY FUEL REACTORS

A. Classification

Slurry fuel reactors may be classified according to the fuel flow arrangement—heterogeneous or homogeneous. Classification may also be as to whether the slurry fuel is stationary, boiling, forced circulating or combinations thereof. Further classification may be as to the function of the slurry in the nuclear or power removal process. Possibilities are fuel, fuel-coolant, fuel-moderator, and fuel-coolant-moderator.

It is evident that a heterogeneous slurry fuel reactor is quite different from a heterogeneous solid fuel reactor because of the two phase condition and the light concentration of fissionable material in the slurry fuel. The usual design of a heterogeneous slurry reactor is that of a system of parallel tubes containing the slurry, surrounded by moderator. The moderator may be liquid or solid and the slurry fuel is utilized for carrying heat. Most previous designs of slurry reactors have emphasized the homogeneous type, although one early Hanford design and a recently proposed design by the Netherlands Reactor Committee were heterogeneous (Table 1, p. 40).

Advantages and disadvantages of the homogeneous and heterogeneous arrangements depend on inovations of the specific design; however, certain criteria indicate possible advantages of each type. The following are advantages of the homogeneous arrangement over the heterogeneous:

1. Fewer neutrons lost, and thus lower enrichment required due to less structural material in the core. Structural materials which are very weak neutron absorbers are desirable but not necessary.
2. Less erosion due to lower velocities and less slurry contact with structural materials.
3. Possibly less radiation damage to structural materials.
4. Less pumping power required.

Advantages of the heterogeneous arrangement are:

1. Less uncertainty in the flow and stability of the slurry. Turbulence induced by high velocity flow through tubes may be used as a means of achieving stability. Matched densities, stabilizing agents, or complicated flow arrangements are not needed. No hot spots as a result of stagnant areas in core and lesser caking of slurry on structural materials both due to higher turbulence.
2. Versatility in the fuel-moderator-coolant arrangement. Slurry need not be a good moderator.
3. Simplicity in design and less critical stress requirements due to the possibility of use of tubes to contain the slurry. Large pressure vessels with high stress concentrations due to entrance and exit holes and due to thermal stresses from absorption of radiation are not required.
4. Less loss of neutrons by streaming due to smaller holes entering and leaving the core (67). This advantage would be more pronounced for a slurry which did not have any moderating ability.
5. Higher power density due to greater velocities.

6. Possibility of providing for non-uniform fuel loading thus achieving a flat flux and even power production. It has been proven both experimentally and theoretically that flat flux is a criteria for minimum critical mass (68,69).
7. Decrease in neutron resonance absorption due to geometry.
8. Possibility of providing for a tube failure by simply plugging it and thus prevent lengthy shut downs for repair.

From the above comparison it would appear that the heterogeneous arrangement has many advantages but that these may be overcome by the disadvantage of greater parasitic loss of neutrons by structural materials and greater erosion.

Most slurry fuel reactor designs have been either the forced circulation or boiling types; however, a liquid metal fuel slurry reactor in which the slurry is stationary has been proposed (Table 1). The boiling slurry reactor may be either stationary or forced circulating. The stationary boiling slurry reactor has been given most of the previous consideration by designers. Stationary and stationary-boiling slurry reactors possess the advantage of lower fuel holdup, less erosion, and lower pumping requirements. The forced circulation slurry fuel reactor possesses the advantage of greater power density and more mechanical and nuclear stability. The boiling slurry reactor is faced with the problem of vapor separation and slurry carry over by foaming.

The function which the slurry will serve in the nuclear or power removal processes depends on the materials suitable for comprising the components of the slurry.

B. Possible Cycles

A slurry power reactor may operate on three possible cycles. It may act as a source of heat which is circulated outside the reactor and passed through heat exchangers or its fluid may be passed directly through the turbines in the power cycle. If the latter is used the reactor may operate either on the Rankine or the Brayton cycles. These possibilities are illustrated by Figure 2.

The Brayton cycle has the disadvantage of requiring high power input to the compressor and high separation efficiency in the separator. The advantage of the Brayton cycle is that it can use inert, non-erosive gases, such as helium, as motive fluid for the solid particles and its outlet temperatures are not limited by pressure.

Many variations of these cycles are possible. The proposed Vapor Slurry Reactor illustrates one possibility.

C. Slurry Reactor Designs

The published designs of slurry fuel reactors are listed in Table 1. The fluidized solid reactors do not strictly fit into the slurry category, but were included because of similarities in the problems involved and because slurries are usually used somewhere in the design for solid transport. A slurry reactor has not been built and, thus, all of these designs are proposals that require additional investigation and experimentation to prove their feasibility. Little appears in the literature on many of the listed designs,

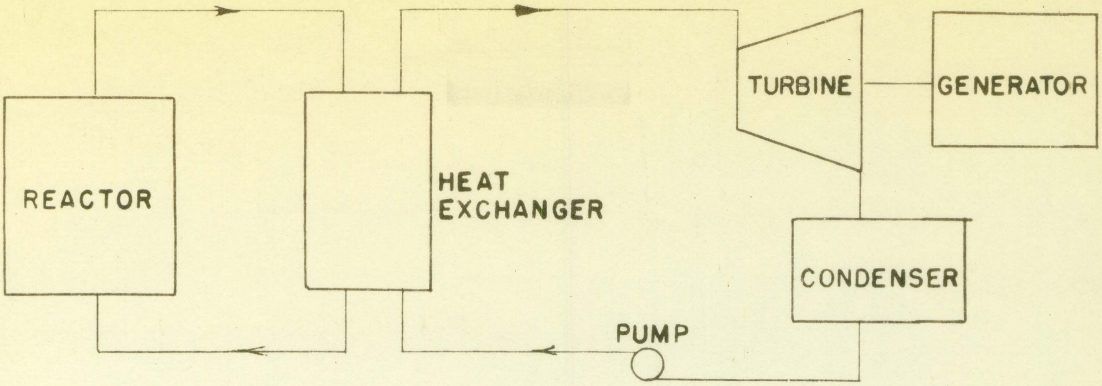

FIGURE 2a. RANKINE CYCLE

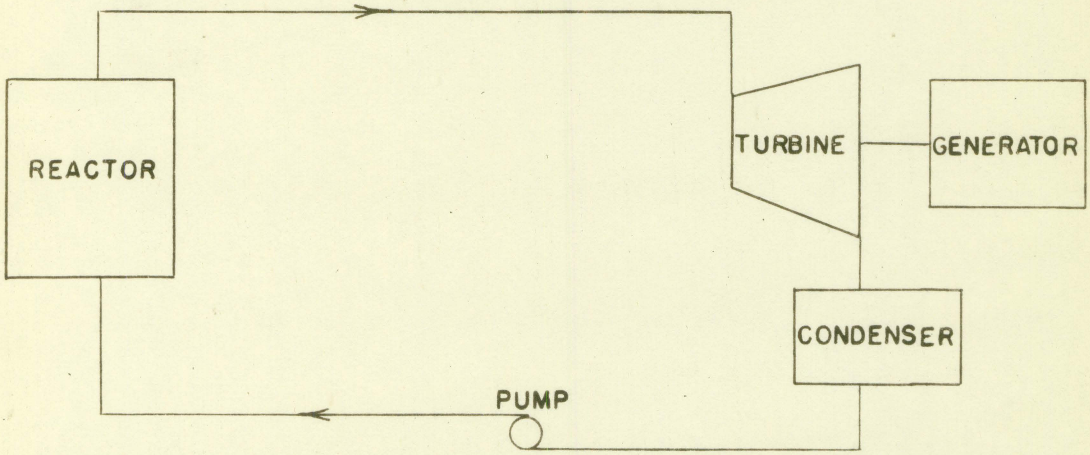

FIGURE 2b RANKINE CYCLE: BOILING SLURRY REACTOR

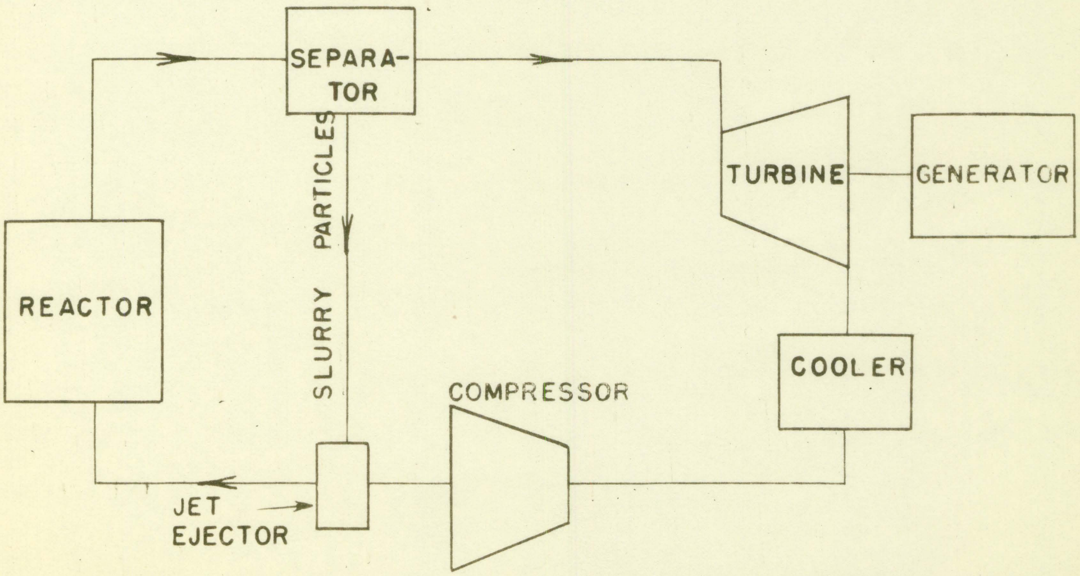

FIGURE 2c. BRAYTON CYCLE: GASEOUS SLURRY REACTOR

FIGURE 2. POSSIBLE SLURRY REACTOR CYCLES

indicating that literature concerning the work done on them was unpublished, or unavailable to the Author.

The chief disadvantages of the aqueous designs are low operating temperatures and high pressures. The good moderating properties, low neutron absorption, and noncorrosiveness of aqueous solutions are advantages of these designs. The homogeneous-boiling-aqueous slurry reactors have difficulty in achieving high power densities and may have trouble with foaming and slurry carry-over.

The intermetallic compound-liquid metal slurry reactor designs utilize the excellent heat transfer properties of liquid metals and are able to operate at high temperatures with low pressures. Several cheap means of processing liquid metal fuels have been proposed and may be prime advantages of these designs. Corrosion is the chief disadvantage that has arisen in development of the liquid metal slurry reactor.

Corrosion by hydroxides is the primary disadvantage of the hydroxide slurry reactor designs. Instability of hydroxide slurries has been mentioned as a limiting feature of these designs, however static settling ability appeared to be the factor that was being considered. The excellent moderating and non-neutron absorbing properties of hydroxides, which allow very small core sizes (70), make the hydroxide reactor desirable when weight is a prime consideration. The hydroxide slurry reactors also possess the ability to operate at high temperatures without high pressures. These reactors might be feasible for a rocket power plant where the time of operation of the reactor would be short and corrosion would not be critical.

The fluidized solid reactors possess the advantages of possible operation at high temperatures with low pressures. The noncorrosiveness of inert

TABLE 1: SLURRY REACTOR DESIGNS

Designation	Slurry Reactor Classification	Slurry	Moderator Core Shape	Coolant Max. Temp.	Reactor Power Power Density Specific Power	References
1. Proposed Hanford Homogeneous Slurry Pile	Homogeneous Forced Circulation Fuel-Coolant-Moderator	Natural U Oxide D_2O	D_2O Sphere	Slurry 248° F	750,000 kw —— ——	22 p. 28; 38;73;75 71 p. 186; 72 p. 27.
2. U^{233}, D_2O Moderated Slurry Pile	Homogeneous Forced Circulating Fuel-Coolant-Moderator	Enriched U-D_2O	D_2O Sphere	Slurry ——	100,000 kw —— ——	71 p. 189; 72 p. 33; 75.
3. Homogeneous Slurry Power Reactor	Homogeneous Forced Circulating Fuel-Coolant-Moderator	Natural UO_3-D_2O	D_2O Sphere	Slurry 482° F	2,000,000 kw 6.85 kw/l ——	71 p. 375; 76.
4. U^{235} Pilot Plant for U^{233} Thermal Breeder	Homogeneous Forced Circulating Fuel-Coolant-Moderator	Enriched U-D_2O	D_2O Sphere	Slurry ——	10,000 kw 0.83 kw/l 6660 kw/kg[a]	71 p. 84; 72 p. 31; 75.
5. Liquid Suspension Reactor	Homogeneous Forced Circulation Fuel-Coolant-Moderator	Natural UO_2-D_2O	D_2O Cylinder	Slurry 572° F	—— —— ——	30.
6. Boiling Slurry Plutonium Power Producer	Homogeneous Stationary-Boiling Fuel-Moderator	Natural UO_3-D_2O	D_2O Sphere	D_2O Vapor 595° F	805,000 kw 4.03 kw/l ——	71 p. 144; 80.

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[a] kg of fissionable material

TABLE 1: (Continued)

	Designation	Slurry Reactor Classification	Slurry	Moderator Core Shape	Coolant Max. Temp.	Reactor Power Density Specific Power	References
7.	Reactor for A Large Naval Surface Vessel	Homogeneous Stationary-Boiling Fuel-Moderator	Natural UO_3-D_2O	D_2O Sphere	D_2O Vapor 482° F	500,000 kw 3.6 kw/l	71 p. 291; 81.
8.	Proposed Hanford Heterogeneous Slurry Pile	Heterogeneous Forced Circulating Fuel-Coolant-Moderator	Natural UO_2-D_2O	D_2O Separate From Slurry Cylinder	Slurry 572° F	———— ———— ————	22 p. 28; 71 p. 187; 72 p. 29; 73.
9.	Internally Cooled Power Breeder	Heterogeneous Stationary Fuel	U^{233} USn_3-Bi,Sn,Pb	Graphite Cylinder	Th_3Bi_5-Bi 968° F	500,000 kw ———— 4500 kw/kg	52;77.
10.	U^{233} Breeder Bismuth Slurry	Heterogeneous Forced Circulating Fuel-Coolant	U^{233}-Bi	D_2O Cylinder	Slurry	200,000 kw ———— ————	71 p. 190; 72 p. 46; 78.
11.	Phosphorus Cooled-Phosphorus Turbine	Heterogeneous Forced Circulating Boiling Fuel-Coolant	Enriched U Phosphate-White Phosphorus	C, Be, or BeO Sphere	White Phosphorus Vapor 1112° F	———— ———— ————	71 p. 371 72 p. 45.
12.	Homogeneous Reactor for Subsonic Aircraft	Homogeneous Forced Circulating Fuel-Coolant-Moderator	Enriched UO_2-NaOH	NaOH Sphere	Slurry 1500° F	270,000 kw 96 kw/l 21,300 kw/kg	71 p. 332 79.

TABLE 1: (Continued)

	Designation	Slurry Reactor Classification	Slurry	Moderator Core Shape	Coolant Max. Temp.	Reactor Power Power Density Specific Power	References
13.	Circulating Fuel-Moderator Slurry Reactor	Homogeneous Forced Circulating Fuel-Moderator	Enriched U Oxide-NaOH	NaOH Sphere	NaOH ——	—— —— ——	71 p. 364;
14.	UO_2 Powder Pile	Heterogeneous Forced Circulating Fuel-Coolant	Natural UO_2-He	Graphite Cube	Slurry ——	—— —— ——	71 p. 78 72 p. 47; 82.
15.	B-B Shot Pile	Heterogeneous Forced Circulating Fuel-Coolant	Natural U-Gas	Graphite ——	Slurry ——	—— —— ——	71 p. 79; 72 p. 48; 83.
16.	ORNL Proposed[b] Fluidized Solid Reactor	Homogeneous Forced Circulating Fuel-Coolant-Moderator	U^{233} Impreg. C-Argon	Graphite Cylinder	Slurry 2000° F	250,000 kw 12 kw/l 2380 kw/kg	65;66
17.	Heterogeneous[b] Fluidized Fuel Reactor	Heterogeneous Forced Circulating Fuel-Coolant	Natural UO_2-Gas	D_2O Cylinder	Slurry 1292° F	—— —— ——	30.
18.	Pile for[b] Chemical Products	Homogeneous Stationary Fuel	Enriched U Carbide Spheres	Graphite Sphere	Hydrocarbon Gases 4140° F	300,000 kw —— ——	71 p. 184; 72 p. 63.
19.	Vapor Slurry Reactor	Heterogeneous Forced Circulating Fuel-Coolant	Enriched UO_2-H_2O Vapor	BeO Cylinder	H_2O Vapor 1025° F	488,000 kw 601 kw/l 1515 kw/kg	

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[b] Does not fit slurry category but was included because of similarities.

gases which may be utilized in these designs and the good heat transfer which results from intimate contact of a gas with the fluidized solid are additional advantages of these designs. Low power density may be a disadvantage. A homogeneous fluidized solid reactor design utilizing a moving fluidized bed (design 16) has been declared unfeasible because of the possibility of large rapid density fluctuations destroying the control of the reactor and because of difficulties that might have resulted from attrition of U^{233} impregnated graphite particles which were incorporated in the design (66). A design proposed by the Netherlands Reactor Committee alleviated the difficulty of density change by making the system heterogeneous (design 17).

D. Other Possibilities

Other possible applications of the slurry in nuclear reactors might be as fertile material and as coolant-moderators.

Because of the difficulty of combining heavy concentrations of thorium with suitable fluids by any other means except slurries and fluidized solids, the slurry presents possibilities for use as a means of suspending fertile material in breeder blankets.

One could visualtize the use of the slurry as a coolant-moderator. For example, if a liquid metal such as bismuth, which is a poor moderator, were used as a reactor coolant, it might be feasible to suspend particles of moderator material such as BeO, Be, or graphite in this coolant to aid in moderation. Such additions would also be effective in reducing the streaming loss of neutrons out of core openings through which a poorly moderating coolant was flowing.

Most of the previous discussions pertain to thermal reactors. Possibilities may also exist for use of slurries for fast reactor fuels.

V. THE VAPOR SLURRY REACTOR

During the investigation of slurries and slurry fuel reactors, the design of a reactor, which was designated the "Vapor Slurry Reactor", was conceived. A description and a preliminary analysis of this reactor are presented on the following pages.

A. Description

The Vapor Slurry Reactor utilizes a fuel consisting of solid particles of fissionable material suspended in a vapor. The flow diagram of the proposed Vapor Slurry Cycle is illustrated in Figure 3. This reactor utilizes the Rankine cycle to convert heat energy to electrical energy. Steam appears to be the most suitable vapor for a thermal reactor, although the cycle is versatile and other vapor media might be used. For the preliminary design a reactor using a vapor slurry composed of H_2O vapor and UO_2 was chosen.

The following is a description of the proposed reactor and refers to the flow diagram in Figure 3. It is assumed that the reactor is thermal, however this is not a limitation of the design. The hot slurry particles and a required amount of recycled vapor are injected into the vaporizer. The hot particles and vapor vaporize the high pressure liquid entering the vaporizer from the feed heaters and feed pumps. The slurry, which is a fissionable

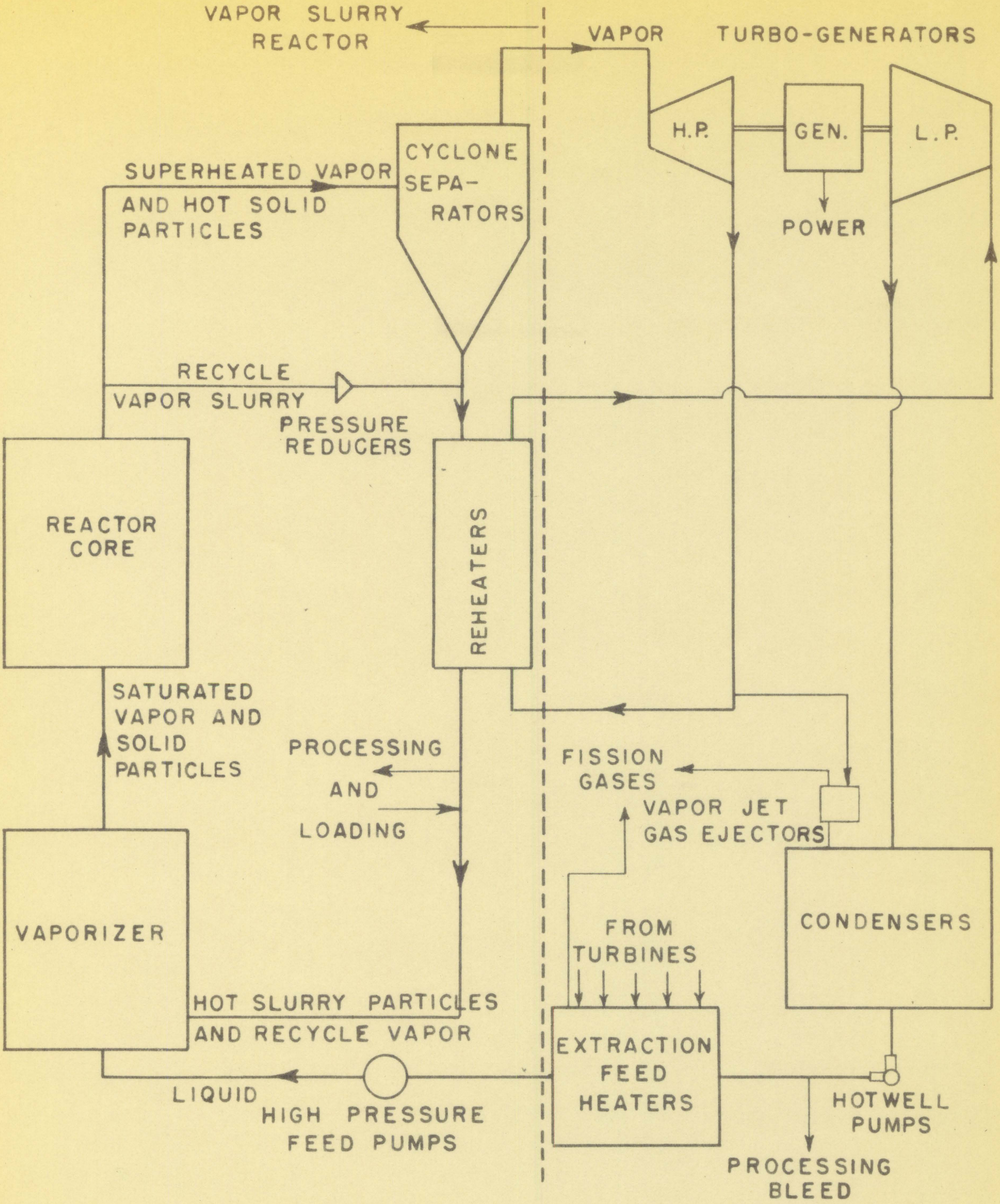

FIGURE 3. THE VAPOR SLURRY REACTOR

solid-saturated vapor mixture, passes from the vaporizer to the reactor and is heated by the resulting nuclear reaction. Thus, the reactor, which consists of a heterogeneous array of tubes surrounded by moderating material, serves to superheat the vapor and heat the slurry particles.

At the reactor outlet part of the slurry is recycled to the vaporizer and the rest continues to the cyclone separators which separate the solids from the vapor. The solids from the cyclone separators are then combined with the recycle slurry and both return through the reheaters to the vaporizer where they act to vaporise water entering from the feed pumps. The solids and recycle slurry are injected into the vaporizer by use of pressure differential, vibration, screw conveyance, or other similar means. Criticality is prevented in the circuits external to the reactor by absence of moderator and by divided flow.

The separated vapor from the cyclones proceeds to the turbines and then to the condensers. Gases can be removed in the condensers by standard vapor-jet-gas ejectors. The condensate from the condensers is pumped through extraction feed heaters to the vaporizer. Additional gases which have been entrained in the condensate can be removed by use of one or more standard deaerating feed heaters.

Bleeds can be incorporated in the condensate and in the reheater sections of the cycle to allow for processing. The concentration of the slurry in the reactor can be controlled by varying the rate of injection of solids into the vaporizer.

The possibility exists for operating the vaporizer as a heterogeneous boiling slurry reactor and thus, eliminate the need for recycling part of the vapor slurry. The large amount of structural material which will necessarily be present in the vaporizer and the possibility for nuclear instability in such a system would most probably rule this proposal out.

The preceding description assumes that radioactive vapor can be passed through the turbines and that high separation efficiencies can be achieved from the cyclone separators. Another possibility would be to pass the vapor or the slurry through desuperheating and condensing heat exchangers. Two versions of this alternative are illustrated in Figure 4. It is believed that the cycle shown in Figure 4a would be more suitable because it eliminates the need for pumping the slurry in the heat exchanger circuit. It also reduces problems of slurry caking in the heat exchangers and slurry erosion in the initial section of the vaporizer, which may be an array of high velocity jet pumps. On the other hand, the system shown in Figure 4b possesses the possibility of using fluidized solid beds to achieve better heat transfer in the desuperheating heat exchangers. Both of the cycles shown in Figure 4 could employ regenerative feedwater heating and reheat just as was proposed for the cycle of Figure 3.

Because of the loss in efficiency in the heat exchangers, the alternative cycles in Figure 4 would be less desirable than the cycle of Figure 3.

B. Feasibility Using Specific Vapor Slurry

In the preliminary analysis that was undertaken on the Vapor Slurry Reactor it was specified that water vapor was to be the vapor component and uranium dioxide the solid component of the vapor slurry. It was assumed that the cycle as shown in Figure 3 would be used.

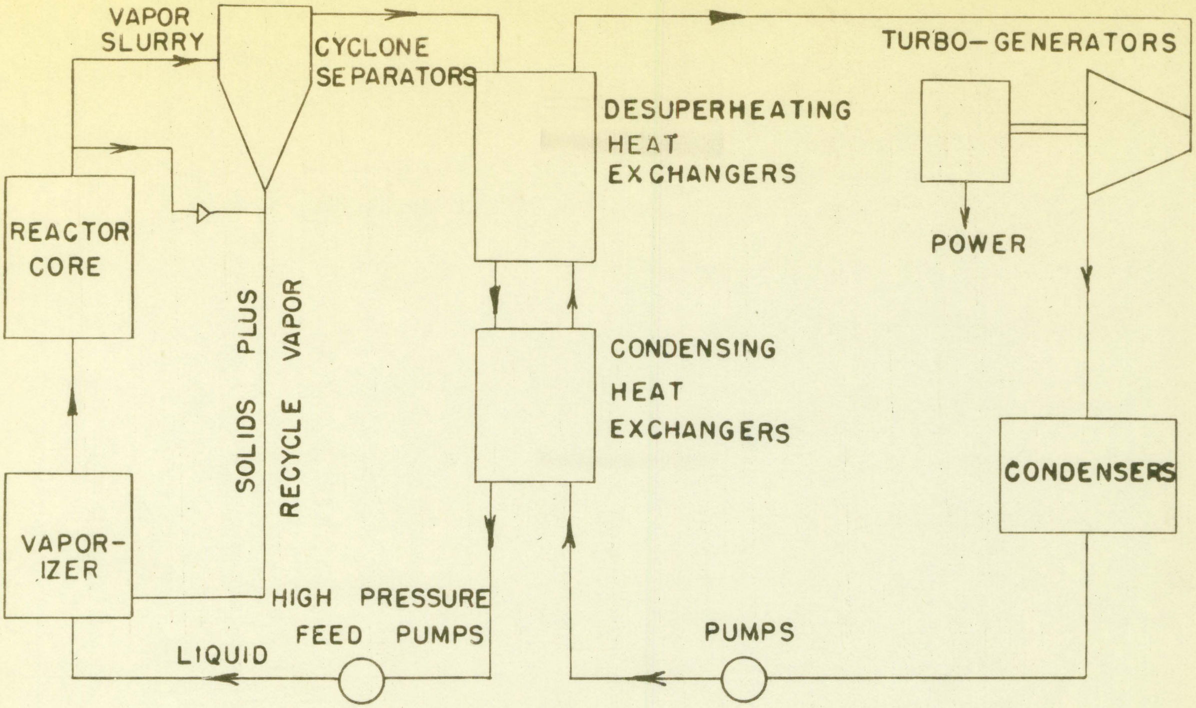

FIGURE 4a. ALTERNATE CYCLE ONE

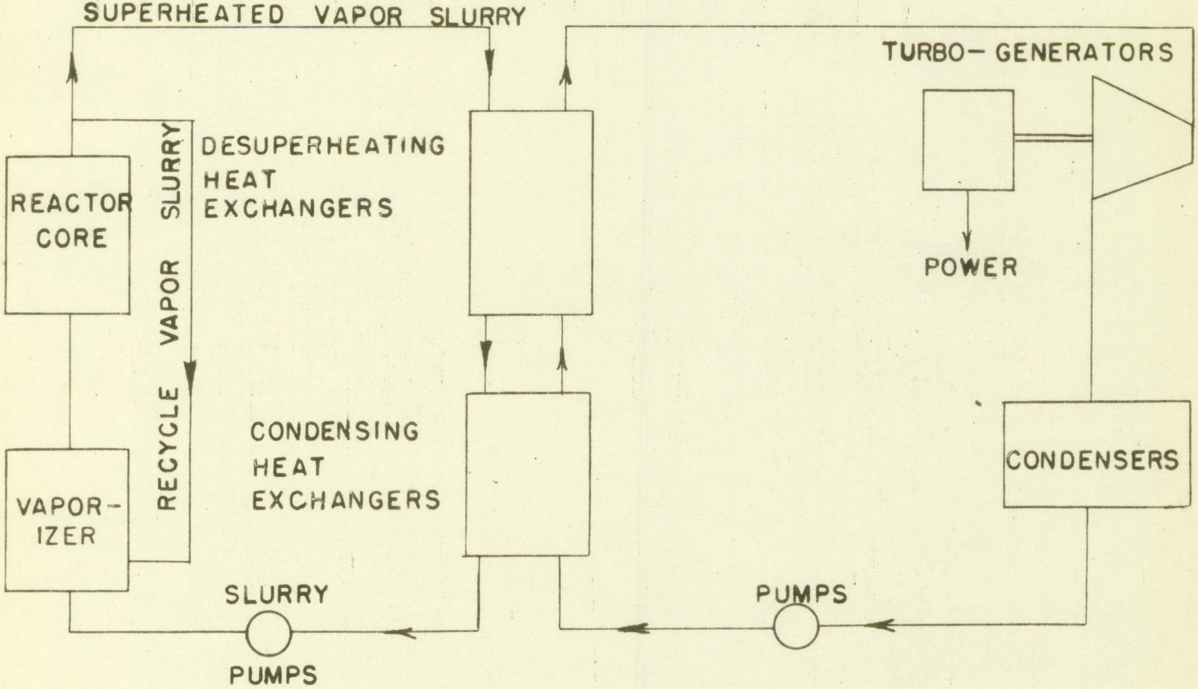

FIGURE 4b ALTERNATE CYCLE TWO

FIGURE 4. ALTERNATE VAPOR SLURRY CYCLES

The Vapor Slurry Reactor (VSR) cycle utilising a steam-UO_2 slurry fuel possesses several advantages over previous aqueous fuel reactor designs.

1. The temperature and pressure at the reactor outlet are limited only by the maximum that slurry and tube materials can withstand. Previous reactor designs utilizing aqueous circulating fuels featured extremely high pressures and comparatively low temperatures in order to prevent the aqueous solution from flashing to steam. The maximum temperature of these designs was limited by the critical pressure of water. The vapor slurry cycle allows production of steam commensurate with modern steam power plant practice (1450 psig and 1000° F).
2. The absence of boiling in the reactor core eliminates instabilities caused by large and rapid bulk density changes and non-uniform fuel flow.
3. The slurry particles do not pass through the pumps. This alleviates many problems concerning pump erosion and bearings.
4. The intimate contact between the slurry particles and the carrying fluid allows for extremely rapid and efficient heat transfer both in the reactor and the vaporizer. Boiling reactor designs with stationary fuel elements are prevented from attaining high superheat because of the poor heat transfer to superheated steam.
5. The heterogeneous flow arrangement in the reactor allows for high fuel velocities, resulting in high power density, and for more accurate prediction of characteristics of fuel flow, resulting in elimination of instabilities which might occur if the reactor were one large tank.

6. The fuel distribution in the reactor may easily be made non-uniform to allow for minimum critical mass.
7. Operation at high temperatures, low pressures, and with reheat prevents turbine erosion due to "wet" vapor.
8. High temperatures and pressures result in high thermal efficiency and greatly reduce the size of the turbines needed.
9. The cycle allows for use of previously developed and standard turbines, condensers, and feedwater heaters with special provisions for sealing and maintance.

Disadvantages and problems which may arise with this design are as follows:

1. Erosion of the tube materials, the cyclones, or the solid particles may cause serious difficulty.
2. Attrition of the slurry particles due to erosion or fission may prevent high separation efficiencies in the cyclone separators, resulting in fines getting to the turbines and condensers. A high pressure drop will be required across the cyclones in order to achieve the necessary separation efficiency.
3. Highly radioactive steam entering the turbine cycle may present difficulties in sealing and maintaining the turbines, condensers, feedwater heaters, and pumps.
4. The entire cycle must be shielded, increasing the total plant weight and cost.
5. Large numbers of neutron absorbing tubes in the core prevent use of natural uranium slurries.

6. Presence of fission gases and steam soluble fission products may increase the corrosiveness of the steam in the turbine cycle.
7. Presence of too much noncondensable gas in the condenser may seriously reduce the heat transfer coefficient (11, p. 342).
8. Caking of the particles on container materials might occur.

Solution of the above problems does not seem unsurmountable. The hardness of UO_2 is reported to be from Moh 3.5 to 4 so that erosion of container materials should not be serious if stainless steel is used throughout the system. Tube bends and other vunerable spots could be lined with hard materials to prevent erosion.

The primary difficulty appears to be that of preventing particles from getting through the cyclone separators. By arranging the separators in both parallel and series, extremely high separation efficiencies can be attained. Particle agglomeration has been achieved by use of sound fields. Stationary wave patterns set up by sound fields preceding the cyclones, in the cyclones, or between two cyclones in series could be used to agglomerate the fine fission or erosion particles and allow their separation. Subsequent turbulence in the reheaters or vaporizer would act to break up large agglomerates which might occur.

The turbines and their associated circuits will undoubtedly become radioactive due to fission gases and soluble fission products. It appears that it might be feasible to submerge the turbines and condensers in water in floodable compartments. The water would act as a shield and would allow easy access for remote repair.

Continuous processing and continuous removal of gases will probably make the problems of additional corrosion and poor heat transfer in the condensers insignificant.

If the problems above are found to be unsolvable, one of the cycles illustrated by Figure 4 could be utilized. Use of finned tubes or some other means of achieving high heat transfer in the desuperheating heat exchangers might make these cycles more feasible than that illustrated by Figure 3, due to less problems with only small decreases in operating efficiency.

By reason of the previously mentioned advantages, the Vapor Slurry Reactor appears feasible and should develop into a competitive type of power reactor.

C. Preliminary Analysis

The following initial conditions were assumed for the preliminary analysis of the Vapor Slurry Reactor using the cycle of Figure 3.

1. The reactor is thermal and the slurry is UO_2-H_2O vapor.
2. The reactor consists of a vertical right circular cylinder composed of a lattice of hexagonal bricks of BeO.
3. In the center of each of the moderator bricks is a 1 in. inside diameter, type 347 stainless steel tube to carry the vapor slurry.
4. The maximum concentration of solids that can be carried through the tubes in the reactor is 2.5 per cent by volume.
5. The diameters of the solid particles range from 10 to 50 microns.
6. There is a negligible temperature differential between the slurry particles and the carrying vapor at the reactor outlet.

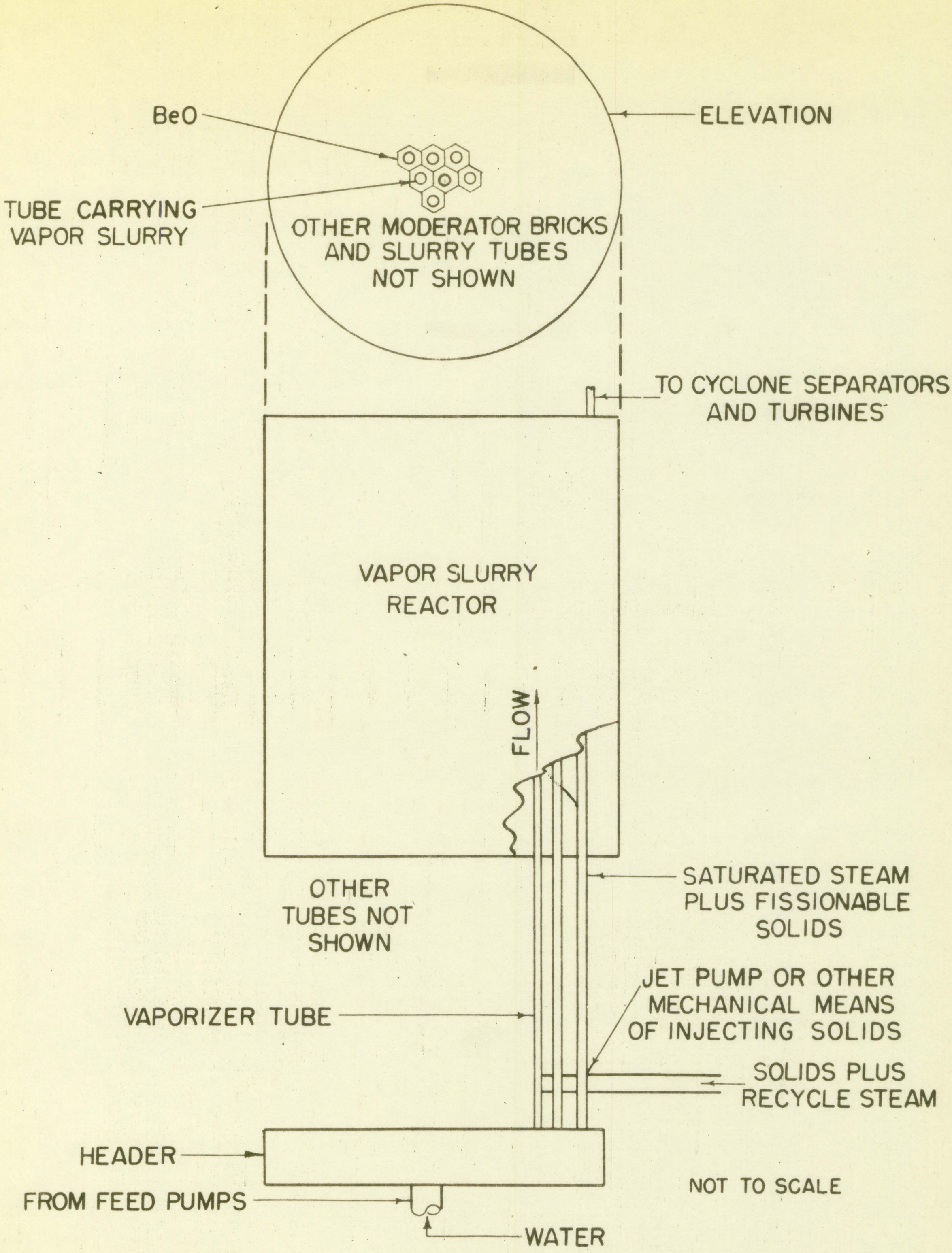

FIGURE 5 POSSIBLE REACTOR CORE AND VAPORIZER DESIGN

7. The mean velocity of the slurry through the reactor outlet is 100 fps.
8. The pressure and temperature drops from the reactor outlet to the turbines are 135 psi and 25° F, respectively.

Tests have indicated that uranium oxides are the most favorable solid components of an aqueous slurry. Uranium dioxide was chosen as the most suitable of the oxides for the vapor slurry because of its high uranium content per unit volume, high heat capacity, and assumed chemical and thermal stability at the reactor operating temperatures. Work at New Brunswick Laboratory on the Green Salt Moving Bed Project (84,85) has provided data from which some indication of what to expect regarding the stability of UO_2 in steam can be obtained. Experiments indicate that the rate of thermal dissociation of 3/16 in. pellets of uranium trioxide (UO_3) to black oxide (U_3O_8) is 5.33×10^{-4} per cent per minute at 662° F in a steam atmosphere. Rates of reduction of 3/16 in. black oxide pellets in steam containing 3.5 mole per cent hydrogen vary from 0.072 per cent conversion per minute at 860° F to 3.08 at 1157° F. These data plus the conclusions of the Netherlands Reactor Committee (30) make it appear that UO_2 will be the most stable oxide for operation in steam at temperatures up to 1025° F.

Use of a D_2O vapor slurry would increase neutron economy; however it was felt that the added cost and problems concerned with heavy water would make its use unjustified for this reactor.

The reactor shape and construction were chosen because of simplicity in this arrangement. The reactor was made vertical because of less erosion from a slurry flowing vertically in comparison to a slurry flowing horizontally.

Beryllium oxide was chosen as moderator because of the ease with which it can be adapted to the assumed core arrangement.

The tube diameter was arbitrarily chosen and a more detailed analysis would be required to specify this parameter. Type 347 stainless steel was chosen because of its excellent properties in aqueous systems as has been proven by various investigators. Stainless steel has the disadvantage of an appreciable neutron absorption cross section. Zirconium, which has very good nuclear properties, is rapidly corroded by high temperature steam. Titanium, which may be more erosion resistant than stainless steel, and which has an abundant isotope with a low absorption cross section (Ti^{50}), absorbs gases rapidly at high temperatures.

The assumed maximum solids concentration was based on the work of Cramp (15). The ratio of the density of the solid to the density of the fluid was 1175 for the grain-air suspensions tested by Cramp. This ratio is about 284 for UO_2 suspended in steam at the average reactor operating conditions, so that the maximum concentration will require experimental verification.

The average range of fission fragments in UO_2 is about 10 microns (30), so that a particle 10 to 50 microns in diameter would allow for a high percentage release. The assumption concerning the negligible temperature differential between the particles and the vapor was based on the small slurry particle size.

The assumed velocity of 100 fps is commensurate with that used in steam superheaters.

The assumed pressure drop from the reactor to the turbines was made conservative because of necessity for high separation efficiencies in the cyclone separators.

The temperature drop of 25° F from the reactor to the turbines was arbitrarily specified as a probable value.

The vaporizer will consist of a heterogeneous array of tubes. The flow into each tube could be achieved by use of jet pumps to decrease the pressure and possibly some mechanical means such as screw conveyance, ultrasonics, or vibration to keep the particles moving and adjust the flow of the solids. An arrangement similar to that proposed by the Netherlands Reactor Committee (30), for keeping fluidized solids moving, might be feasible. The design of the vaporizer depends on experiment and therefore, was not attempted.

1. Thermal Analysis

A detailed thermal analysis is presented in the appendix. A summary of the assumptions, method of attack, and results follows here.

It was specified that the reactor must supply steam at 1450 psig and 1000° F to two 90,000/100,000 kw preferred standard* turbine generators operating with 1000° F/1000° F reheat and five stage extraction, regenerative feed water heating. The cycle was designed for a maximum condenser pressure of 2.50 in. of Hg absolute and for the turbo-generators operating

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* Refers to preferred standard turbine conditions as agreed upon by a joint committee of ASME and AIEE (86).

at 10 per cent above rated load or 100,000 kw. Table 2 lists the preferred standard data which were used for cycle design.

Table 2: PREFERRED STANDARD CONDITIONS

Exhaust pressure	2.50 in. Hg abs.
Per cent rated load	110
Reheat pressure	436 psia
Feed water temperature	443° F
Throttle steam rate	6.86 lb/kw-hr
Reheater steam rate	6.13 lb/kw-hr
Heat added in reheater	161.7 Btu/lb

The thermal analysis was begun by starting at the throttle of the turbines and working backward. The conditions at the outlet of the reactor were assumed on the basis of the requirements of the turbines. The conditions at the inlet of the reactor were determined by calculating an approximate pressure loss across the reactor and assuming saturated steam at the outlet of the vaporizer. A conservative pressure loss of 57 psi was determined. After these conditions were specified, heat balances were run on the various components of the reactor cycle.

A heat balance on the reactor with the above assumed initial conditions indicated a heat power of 488,000 kw was needed in order to attain 200,000 kw of electrical power from the turbo-generators.

In the heat balances that were calculated for the cycle components the solid and fluid components were considered separately. The enthalpy of uranium dioxide can by expressed as a function of temperature by the following equation (22,87):

$$h_T - h_{298.16} = 19.77\,T + 0.546 \times 10^{-3} T^2 + 4.68 \times 10^5 T^{-1} - 7513$$

where T is expressed in degrees K and h is expressed in gm-cal/mole. A summary of the cycle conditions is shown in Figure 6.

The volume concentration in the recycle or reheater loop is 3.74 per cent. It was assumed that this concentration will be adequately carried because of lower velocity, downward flow, and possibly larger tubes.

2. Criticality Analysis

The Fermi age treatment was used to obtain an approximate picture of the criticality of the Vapor Slurry Reactor. The critical radius was calculated as a function of the ratio of atoms of beryllium oxide to atoms of uranium 235, assuming a bare unreflected reactor.

Because of its comparatively high pressure, the steam had an appreciable affect on reactor criticality. A rigorous treatment of the problem was not attempted because of the difficulty involved with a heterogeneous--homogeneous arrangement. In the Vapor Slurry Reactor moderator is present within the slurry as well as outside of the slurry and the slurry is flowing heterogeneously through the reactor core. Criticality calculations were made such that a homogeneous mixture was assumed; yet, the volumes of the various components in the reactor were corrected for by expressing the atom or molecule density of each material in atoms or molecules per cm^3 of reactor.

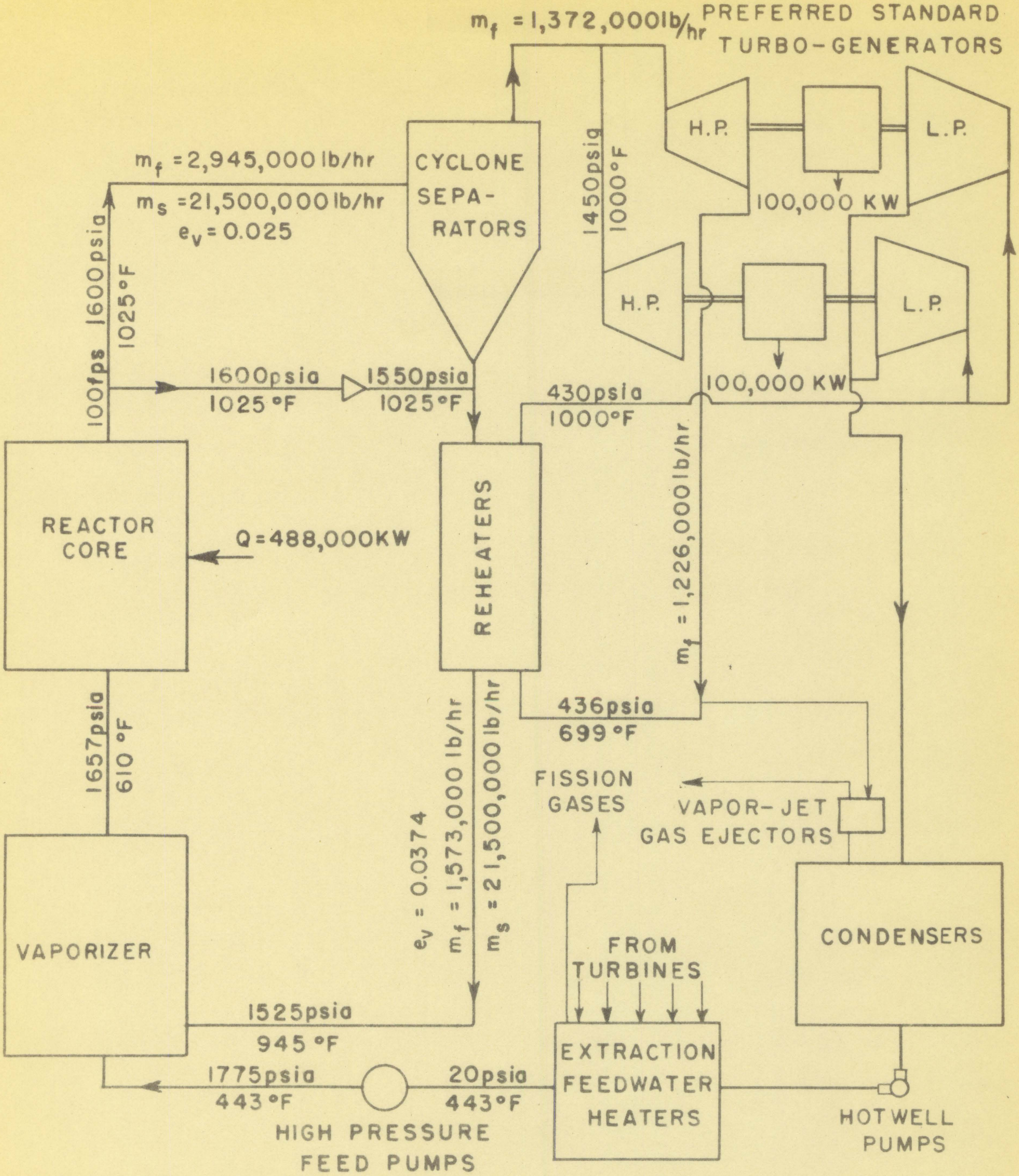

FIGURE 6. PRELIMINARY DESIGN--THERMAL CONDITIONS

The reactor was assumed to be at an average temperature of 840° F and 1650 psia. Neutron cross sections were assumed to vary as 1/v and have a Maxwell distribution. The method of Reference 70 was used for taking into account the effect of chemical binding of hydrogen in the water molecule on the thermal scattering cross section of steam.

It was assumed that the concentration of the fissionable material in each ring of tubes was varied, and a flat flux was established radially across the reactor. It was previously assumed that the solids concentration was constant at 2.5 volume per cent throughout the core so that these two assumptions conflict somewhat. Some difficulty might result from the fact that the velocity of the slurry was changing axially throughout the reactor. For the assumed conditions the velocity varied from approximately 50 fps at the reactor inlet to 100 fps at the outlet and changes in velocity could bring about changes in slurry concentration. This might be corrected by use of tubes whose area increased with distance from the reactor inlet.

An enrichment of 16.67 per cent ($N_{U5}/N_{U8} = 0.2$) and a molecules of BeO to atoms of U^{235} ratio of 3860 were calculated for the representative design. Selection of these values gave a critical radius of 3.25 ft and a reactor height of 6 ft. A detailed summary of the criticality analysis is presented in Appendix C. The results of the criticality calculations are illustrated in Figure 7.

A reflector would undoubtedly be incorporated in the final design of the Vapor Slurry Reactor; however, detailed calculations on core reduction due to reflector did not seem warranted for the preliminary design. Rough calculations indicated that a graphite reflector would provide a reflector savings of about 1.25 ft.

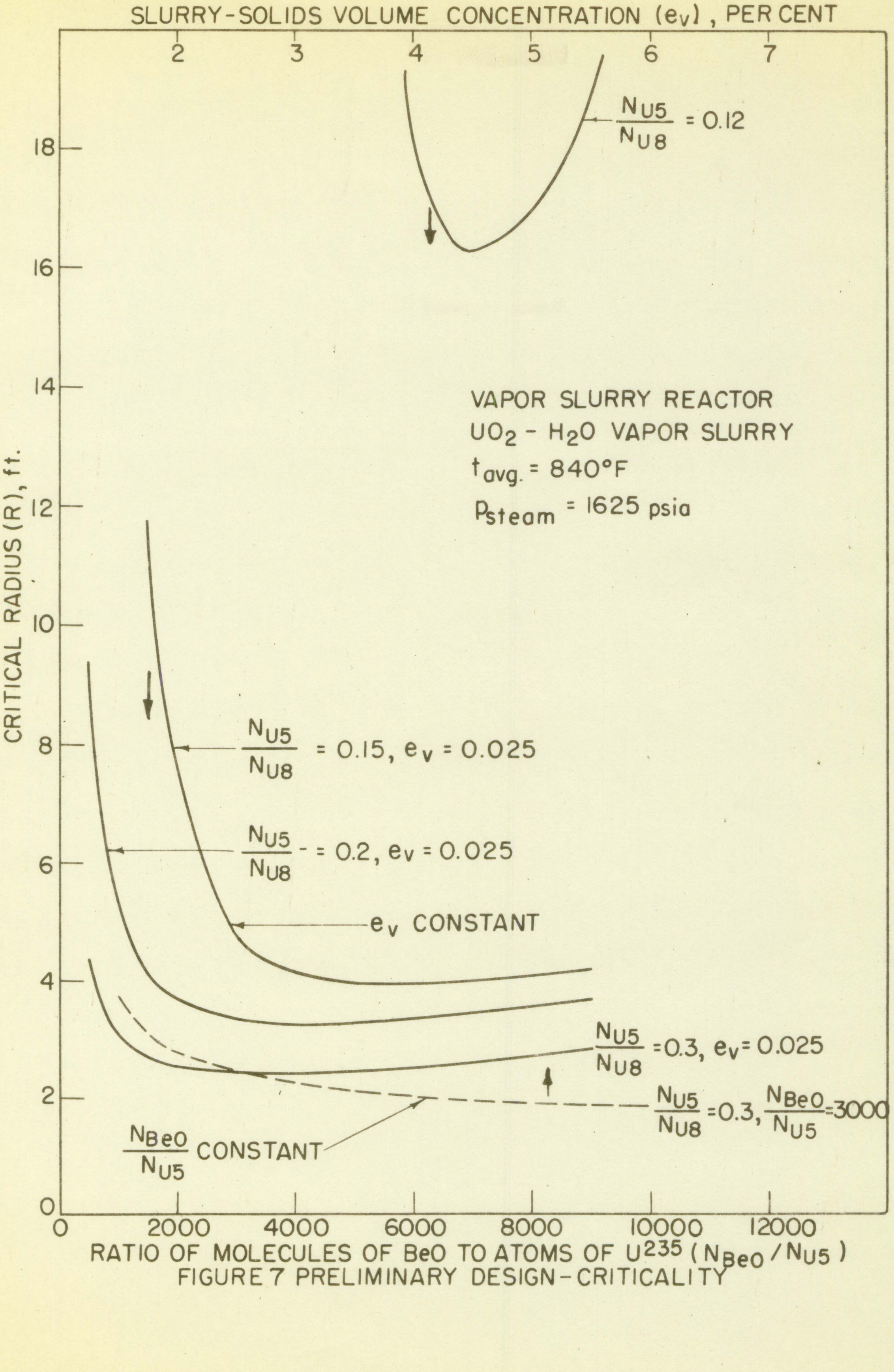

FIGURE 7 PRELIMINARY DESIGN-CRITICALITY

3. Summary of Results

The results of the criticality and thermal analyses are summarized by Table 3. It should be noted that these analyses were conducted assuming that the turbo-generators were operating at 10 per cent above rated power and with an exhaust pressure of 2.50 in. Hg. Thus, the analyses describe the reactor at its maximum power output for the assumed turbo-generators.

Comparison of the Vapor Slurry Reactor with several previous designs is presented in Table 4. It can be seen that the VSR's power density is excelled only by the fast reactor proposals. Although, due to neutron losses in the structural materials the specific power of the VSR is not too high, a greater per cent of the heat power is converted to electrical power. If the specific power were computed on the basis of electrical power produced, the VSR design would compare favorably with the others.

All factors taken into consideration, the VSR appears feasible and its development appears to depend primarily on the promotion of mechanical processes. If the specified temperature, pressure, and velocity conditions prove to be too severe, they could be reduced considerably and the reactor would still possess many advantages. Steam power plants have been designed to operate at supercritical conditions of 5000 psia and 1150° F (90) and the VSR could possibly be designed for such operation provided the necessary materials could be developed.

TABLE 3: SUMMARY OF PRELIMINARY DESIGN

Heat Power	488,000 kw
Electrical Power	200,000 kw
Specific Power	1515 kw/kg of U^{235}
Power Density	601 kw/l
Per Cent Rated Power	110
Average Flux	5.83×10^{14} n/cm^2/sec
Moderator	Hexagonal BeO bricks
Enrichment	16.67 per cent
Molecules of BeO per Atom of U^{235}	3860
Core Shape	Right circular cylinder
Core Diameter	6.5 ft.
Core Height	6 ft.
Number of Tubes	877
Tube Thickness	1/32 in.
Tube Material	347 stainless steel
Vapor Slurry at Core Inlet	1657 psia, 601° F
Vapor Slurry at Core Outlet	1600 psia, 1025° F
Core Volume Concentration	2.5 per cent solids in slurry
Core Flow Rate	24.45×10^6 lb slurry/hr
Core Outlet Velocity	100 fps
Steam at Throttle	1450 psig, 1000° F
Throttle Flow Rate	1.372×10^6 lb steam/hr
Condenser Pressure	2.50 in Hg

TABLE 4: POWER REACTOR COMPARISON

Reactor	Reactor Power Mw	Electrical Power Mw	Power Density kw/l	Specific Power kw/kg[a]
Vapor Slurry Reactor (VSR)	488	200	601	1515
Submarine Intermediate Reactor (SIR)	62.5	15	498	3570
Submarine Thermal Reactor (STR-Mark I)	70	15	210	6950
Pressurized Hanford	500	102	1.3	537
Pressurized Water Reactor (PWR)	232	60	91.2	1400
Plutonium Power Breeder Reactor (KAPL-PPBR)	500	175	644	2500
Bechtel-Pacific Gas and Electric Fast (BP-2)	500	155	708	1535

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[a] kg of fissionable material

D. Other Considerations

1. Reactor Startup and Shutdown

Several procedures are possible for starting the Vapor Slurry Reactor. One possibility would be to derive enough steam from an external source to operate the vaporizer. This is undesirable as it would result in an appreciable extra plant cost and would be unsuited for mobile applications.

Possibly a more desirable method would be to operate the reactor as a heterogeneous boiling slurry reactor until the desired power level was reached. The flow to the cyclone separators would be shut off until enough heat was generated to provide for saturated steam at the vaporizer outlet. Introducing a water slurry into the core instead of a steam slurry would result in a smaller critical size. This could be compensated for by shutting off the flow of the slurry in certain tubes or by decreasing the concentration of the fissionable solids in the slurry. Experience would determine which of these was more favorable.

The reactor could be shut down by dumping the slurry particles into a series of tanks or into fluidized solid beds where the particles could be prevented from caking. The solids could be purged from the system by a high pressure, inert gas.

2. Reactor Control

The Vapor Slurry Reactor could be controlled by varying the concentration of the solids in the slurry, or by cutting off flow of the slurry in certain reactor tubes. Various other possibilities such as use of control rods undoubtedly exist.

Calculations indicated that if it is assumed that the average velocity of the solids throughout the cycle is 50 fps and that the solids travel an average path of 30 ft external to the reactor core, the probability that a delayed neutron will be released within the reactor is 0.157 for U^{235} fissionable material. Thus, it is seen that only 16 per cent of the available delayed neutrons will aid in control of the reactor.

Investigation of the kinetics of circulating fuel reactors has indicated that the negative temperature coefficient makes the reactor inherently stable even without the damping from delayed neutrons (91). It has also been demonstrated that the circulation of the fuel causes damping of power oscillations in the reactor (92). These analyses assumed that the inlet temperatures of the fuel remained fixed while this may not be the case for the VSR. Increases in temperature at the reactor outlet will be fed back to the reactor inlet. A control mechanism operating on the basis of the steam conditions at the vaporizer outlet and varying the concentration of the slurry would provide a method of controlling reactor power.

If the flow of steam to the turbines were decreased at the throttle, less steam would flow through the cyclone separators and more would be recycled to the vaporizer. The vaporizer would then produce superheated steam. If the negative temperature coefficient of the reactor were not great enough to decrease the reactor power sufficiently, the temperature at the reactor outlet would increase. Feedback of this temperature increase to the vaporizer would magnify the situation and possible burnup of the reactor could result. A dump valve preceding the turbine throttles could be used to alleviate this difficulty. When the throttle was closed, the dump valve would open, releasing steam to a tank or to the condensers and maintaining constant flow of steam through the cyclones. The dump valve could then be slowly closed while the reactor control devices decreased reactor power.

A reactor emergency could be met by stopping the flow of solids and fluid into the vaporizer and purging the reactor core with a high pressure inert gas.

A positive means of controlling the Vapor Slurry Reactor could be established and control does not appear to be a limiting feature of the design.

3. The Cyclone Slurry Reactor

There are other possible core designs suitable for the Vapor Slurry Cycle. A reactor which operates similarly to the cyclone furnace might prove feasible. The slurry particles and vapor would be whirled at high velocity through the core by a tangential stream of secondary vapor. The more dense solid particles would be thrown to the outside of the core where they would form a dense, rapidly moving layer in which fission could take place. If the reactor was thermal, a moderator island might be introduced to the center of the core to aid in moderation.

This arrangement would have the advantages of simplicity and extremely high power density. The chief difficulties to be solved would be erosion and possible nuclear instability due to rapid density fluctuations in the whirling cyclone. This reactor might be especially suited for operation with supercritical steam.

4. Fast Reactor

The possibility of operating the Vapor Slurry Reactor as a fast reactor should not be overlooked. A slurry of a fissionable solid suspended in mercury vapor would be a possible fuel. The fast reactor is plagued by the difficulty of removing heat from the core and a slurry utilizing a non-moderating vapor or gas might provide an adequate solution to the problem.

The fast reactor might utilize the Cyclone Slurry Reactor to advantage. The layer of fissionable particles at the external part of the whirling cyclone would provide a dense region in which fast fission could take place.

5. Other Cycles

A slurry reactor operating on the Brayton cycle (Figure 2) might prove feasible. Although the Brayton cycle is less efficient than the Rankine cycle, inert non-corrosive gases which are adaptable to this cycle might make its use feasible. Fluidized solid heat exchangers intermediate to turbines operating on the Rankine cycle might improve the feasibility of gaseous slurry reactors.

The Cyclone Slurry Reactor as previously described could fit into cycles utilizing inert gases as the carrying fluid for the slurry. This reactor might also utilize a liquid as the fluid component of the slurry.

The cyclone slurry reactor core, the heterogeneous slurry reactor core or other forms of slurry reactor cores utilizing a high degree of turbulence to maintain suspension of the slurry appear to be the more feasible form of slurry reactor. An exception to this is the liquid metal slurry reactor utilizing a solid and fluid with matched densities.

VI. CONCLUSIONS

The original purpose of this thesis was to analyze information pertaining to slurry reactors and to present the design of a possible future type of reactor. The following conclusions appear to be valid as a result of the analysis.

1. Further investigation of mechanical means of handling slurries is warranted. Turbulence as a means of achieving slurry stability should not be overlooked. Unique methods of controlling slurry variables, such as ultrasonics, appear to warrant further investigation.
2. The heterogeneous slurry reactor possesses many advantages and should not be excluded from consideration.
3. Gaseous or vapor slurries for reactors have received little or no consideration and appear to warrant investigation. The Vapor Slurry Reactor which was analyzed in this thesis and the suggested Cyclone Slurry Reactor (p. 68) appear to be promising and utilize fuels of this type.
4. Slurries should not be neglected when considering fuels for fast reactors. Intimate contact between the slurry particles may provide a practical means of removing heat from fast reactor cores. The possibility of preparing slurries which contain large percentages of fissionable material also presents advantages for fast reactors.

5. The Vapor Slurry Reactor design appears to be a feasible future reactor type. The primary problems of the ideal cycle illustrated in Figure 3 seem to be difficulties concerned with achieving high separation efficiencies in cyclone separators and with passing radioactive steam through turbines. From the standpoint of overall plant cost the Vapor Slurry Cycle illustrated in Figure 4a may prove to be more suitable because it alleviates these difficulties. The preliminary thermal and criticality analyses which were conducted assuming a steam-uranium dioxide slurry and using Figure 3 gave results which compared favorably with the operating conditions of other power reactor designs. The feature of producing steam with a high degree of superheat appeared to be the primary advantage of this proposed reactor.

VII. ACKNOWLEDGEMENT

The Author wishes to thank Dr. Glenn Murphy whose advice was very helpful throughout the work on this report and whose suggestion as to the possibility of a heterogeneous slurry reactor led to consideration of the Vapor Slurry Reactor design.

VIII. APPENDIX A. NOTATIONS

A. Physical

1. Alphabetical

A	Area, ft^2
C_p	Specific heat at constant pressure, Btu/lb-° F
D	Tube diameter, ft
d	Particle diameter, ft
e_s	Weight concentration of solids in slurry, lb of solid/lb of mixture
e_v	Volume concentration of solids in slurry, ft^3 of solid/ft^3 of mixture
f	Pressure loss friction factor
g	Gravity constant, 32.2 ft/sec^2
H	Height of reactor, ft
h	Enthalpy, Btu/lb
h_c	Surface coefficient of heat transfer, Btu/hr-ft^2-° F
k	Thermal conductivity, Btu/hr-ft^2-° F/ft
L	Length
m	Mass rate of flow, lb/hr
Nu	Nusselt number, h_c/Dk
Pr	Prandtl, C_p /k
P	Pressure, lb/in^2
ΔP	Pressure differential

Q	Heat flow, Btu/hr or Kw
R	Radius of reactor core,
Re	Reynolds number, $\rho v D/\mu$
r	Roughness of tube
SG	Specific gravity
T	Temperature, ° K
t	Temperature, ° F
U	Overall heat transfer coefficient, Btu/hr-ft^2-° F
V	Volume, ft^3
V_p	Specific volume, ft^3/lb
υ	Velocity, fps
z	Reciprocal of the ratio of the pressure drop of the slurry to the pressure drop for pure water flowing at the same velocity

2. Greek

α	Slurry solids distribution factor
μ	Viscosity, lb/ft-sec
ρ	Density, lb/ft^3

3. Subscripts

f	For fluid*
i	For inside of tube
m	For mixture or slurry

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* Absence of a subscript also indicates fluid

o	For outside of tube
s	For solid slurry particles

B. Nuclear

1. Alphabetical

A	Moleculor or Atomic weight
B_m	Material buckling, cm^{-2}
$\overline{\cos\theta}$	Average cosine of the scattering angle per collision
E	Energy, Mev or ev
f	Thermal utilization factor
k_∞	Infinite multiplication factor
L	Thermal diffusion length
L_s	Slowing down length
N	Number of molecules or atoms per cm^3 of reactor
N_x	Number of molecules or atoms per cm^3 of material considered
n	Neutrons
p	Resonance escape probability
W	$1 - \overline{\cos\theta}$

2. Greek

ϵ	Fast fission factor
η	Average number of fast neutrons emitted per thermal neutron capture in fuel

θ	Scattering angle in the laboratory system
λ	Mean free path, cm
ν	Average number of fast neutrons emitted per thermal neutron fission
ξ	Average loss in the logarithm of the neutron energy from an elastic scattering collision
Σ	Macroscopic cross section, cm^{-1}
σ	Microscopic cross section, cm^2 or barns
σ_{eff}	Effective resonance absorption cross section
τ	Fermi age, cm^2
ϕ	Neutron flux, $n/cm^2/sec$

3. <u>Subscripts</u>

a	For absorption
f	For fission
s	For scattering
t	For type 347 stainless steel
tr	For transport
U5	For uranium 235
U8	For uranium 238

IX. APPENDIX B. THERMAL ANALYSIS OF VAPOR SLURRY REACTOR

The thermal analysis has been previously summarized in the text of the report. The analysis was conducted assuming the following preferred-standard conditions:

Turbo-generators	2--90,000/100,000 kw
Per Cent Rated Load	110
Steam Temperature at Throttle	1000° F
Throttle Pressure	1450 psia
Throttle Steam Rate	1,373,000 lb/hr
Reheat Temperature	1000° F
Reheat Pressure	436 psia
Reheater Steam Rate	1,226,000 lb/hr
Heat Added in Reheater	161.7 Btu/lb
Condenser Pressure	2.50 in Hg
Condenser Steam Rate	992,000 lb/hr
Number of Extraction Heaters	5

It was assumed that the components of the vapor slurry are UO_2 and H_2O vapor. A maximum solids concentration of 2.5 per cent was assumed. It was assumed that the steam at the reactor inlet is saturated and that the pressure and temperature at the reactor outlet are 1600 psia and 1025° F, respectively. Average conditions of 1625 psia and 840° F were assumed for the reactor. The specific gravity of UO_2 was assumed to be 10.96. It was

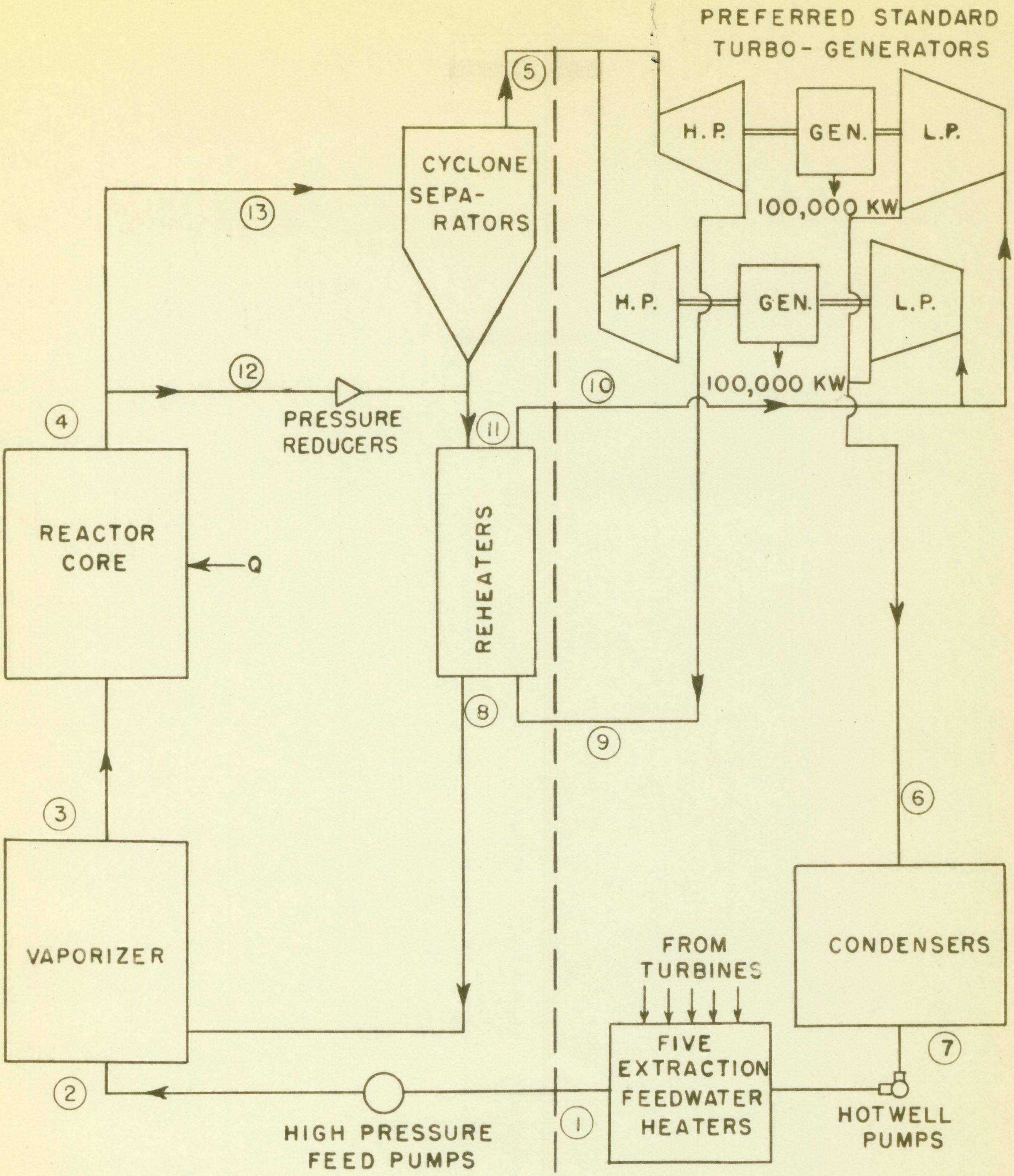

FIGURE 8. PRELIMINARY DESIGN--THERMAL CONDITIONS

assumed that a reactor tube diameter of 1 in. and a reactor outlet vapor velocity of 100 fps are most practical. The neutron economy is affected by the velocity and size of the tubes. The velocity affects the loss of delayed neutrons from the core which in turn affects the neutron economy and control characteristics of the reactor. A high velocity is desirable from the standpoint of high power density and low fuel holdup. The velocity also affects the concentration of solids which can be carried by the steam and affects particle and tube erosion. The diameter of the tube affects friction loss, erosion, and tendency to clog. It also affects loss of neutrons by streaming. The nuclear aspects of the reactor are affected by size, number, and spacing of the tubes. It was assumed that the reactor is 10 ft. high.

The numerical subscripts used throughout the analysis correspond to those indicated by Figure 8.

A. Reactor Power

It was assumed that there were zero losses in the vapor slurry cycle and that the effect of outlet and inlet velocities on the heat balance was negligible. A heat balance yields:

$$Q + m_9 h_9 + m_2 h_2 = m_5 h_5 + m_{10} h_{10} \qquad m_9 = m_{10}$$

$$m_5 = m_2$$

$$Q = m_{10}(h_{10} - h_9) + m_5(h_5 - h_2)$$

$$= 1{,}226{,}000\,(161.7) + 1{,}372{,}000(1489.6 - 422.3)$$

$$= 488{,}000 \text{ kw}$$

where Q is the heat power required from the reactor.

B. Pressure Drop in Reactor

The pressure drop in the reactor results from

1. Friction of vapor slurry on pipe walls
2. Loss of momentum in keeping solids in suspension
3. Losses required to support steam and solids.

1. Friction Loss

It was assumed that the Fanning equation would give a suitable approximation for this case. The equation is as follows:

$$\Delta P_1 = 4f\left(\frac{H}{D}\right)\left(\frac{\rho v^2}{2g}\right) \qquad (11)$$

To obtain a conservative approximation it was assumed that the standard Reynolds correlation holds provided the density of the mixture is replaced with the density of the fluid.

It can be shown that

$$\rho_m = \frac{1 + \frac{m_s}{m_f}}{1/\rho + \frac{m_s}{m_f \rho_s}} \qquad (12)$$

$$e_v = \frac{1}{1 + \frac{m_f \rho_s}{m_s \rho_f}} \qquad (13)$$

$$e_s = \frac{1}{1 + \frac{m_f}{m_s}} \qquad (14)$$

Substitution of the assumed parameters into equations 12, 13, and 14 yields

$$\frac{m_s}{m_f} = 7.3$$

$$\rho_m = 19.4 \ \mathrm{lb/ft^3}$$

$$e_s = 0.88$$

The Reynolds number is

$$R_e = \frac{\rho_m D v_m}{\mu} = \frac{(19.4)(1)(100)}{32.2\,(12)(7.37)\,10^{-7}} = 6,810,000$$

From McAdams (11, p. 155) for flow in smooth pipes

$$\frac{1}{\sqrt{f}} = 4.0 \ \log_{10}(R_e\sqrt{f}) \ - 0.4$$

A trial and error solution of this equation yields f = 0.004

Therefore, substitution into Equation 11 yields

$$\Delta P_1 = \frac{4\,(0.004)(10)(12)(19.4)(100)^2}{1\,(64.4)(144)}$$

$$= 40.1 \ \mathrm{psi}$$

2. Momentum Loss

It was assumed that there is a 5 per cent slip between the solids and vapor at the reactor outlet and 10 per cent slip at the reactor inlet. Empirical data are needed to verify this and no such data exist for particles as heavy as UO_2 flowing in a vertical pipe. Lapple (1, p. 140) states that the slip velocity may be estimated to be equal to the choking velocity which can be expressed by the relation

$$v_{co} = 205\left(\frac{SG}{SG+1}\right) d^{0.6} \tag{15}$$

This relation is not too accurate because the velocity of the solid has been shown to approach that of the fluid as the velocity of the mixture increases. If it is assumed that an average particle diameter of 20 microns is suitable, Equation 15 yields a slip velocity of 6.76 fps which agrees fairly well with the assumed value of 5 fps. The above slip velocity assumptions are practical provided the solids are accelerated to the carrying velocity at the reactor inlet. If this is not the case the predicted momentum pressure loss will be too low.

A momentum balance on the slurry flowing through the reactor is as follows:

$$m_{f3} v_3 + m_{s3} v_{s3} + P_3 A_m = m_{f4} v_4 + m_{s4} v_{s4} + P_4 A_m$$

$$P_4 - P_3 = \Delta P_2 = \frac{m_f v_4}{A_m g}\left[\left(1 - \frac{v_3}{v_4}\right) + \frac{m_s}{m_f}\left(\frac{v_{s4}}{v_4} - \frac{v_{s3}}{v_4}\right)\right] \tag{16}$$

From the continuity equation

$$v_{s3} = \frac{V_{p3}}{V_{p4}} v_4 \cong 0.547 v_4$$

From the slip velocity assumptions

$$v_{s3} = 0.9 v_3 = 0.493 v_4$$

$$v_{s4} = 0.95 v_4$$

A_m in Equation 16 must be the total area of all the tubes. From a previous determination the mass rate of mixture flow (m_m) and mass rate of fluid flow (m_f) were found to be approximately 21,300,000 lb/hr and 2,630,000 lb/hr, respectively. If it is assumed that the average velocity of the mixture is approximately equal to the average velocity of the fluid

$$A_m = \frac{m_m}{\rho_m v_m} = \frac{21{,}310{,}000}{(19.4)(77.3)(3600)}$$

$$= 3.95 \text{ ft}^2$$

Substitution into Equation 16 gives the momentum pressure loss

$$\Delta P_2 = \frac{(2{,}360{,}000)(100)}{(3600)(3.95)(32.2)(144)}\left[(1 - 0.547) + 7.3(0.95 - 0.493)\right]$$

$$= 15.1 \text{ psi}$$

3. Pressure Loss to Support Steam and Solids

This pressure drop is equal to the density of the mixture times the height of the reactor. Thus

$$\Delta P_3 = \rho_m H = \frac{19.4(10)}{144} = 1.35 \text{ psi}$$

Therefore, the total pressure loss in the reactor is

$$\Delta P_{total} = \Delta P_1 + \Delta P_2 + \Delta P_3$$

$$= 40.1 + 15.1 + 1.35$$

$$= 57 \text{ psi}$$

Then

$$P_3 = P_4 + \Delta P_{total} = 1600 + 57 = 1657 \text{ psia}$$

Because the assumed reactor height was greater than that determined in the nuclear analysis and because the simplifying assumption was made for the friction pressure loss, 57 psi is undoubtedly too conservative. However, the assumed pressure drop across the cyclones may be too low due to the high separation efficiency that will be required, so that a conservative result may be justified. A small change in the required pressure at the reactor inlet has little affect on the thermal conditions of the Vapor Slurry Cycle.

C. Reactor Heat Balance

A heat balance of the reactor core allows determination of the rate of flow of the vapor and solids. The following conditions are specified:

$Q = 1.66 \times 10^9$ Btu/hr

$P_4 = 1600$ psia, $t_4 = 1025°$ F

$P_3 = 1657$ psia, $t_3 = 601°$ F

It was assumed that the solid and vapor components of the slurry can be treated separately. A heat balance across the core yields

$$Q + m_f h_3 + m_s h_{s3} + m_s \frac{v_{s3}^2}{2gJ} + m_f \frac{v_3^2}{2gJ} = m_f h_4 + m_s h_{s4} + m_s \frac{v_{s4}^2}{2gJ} + m_f \frac{v_4^2}{2gJ}$$

$$\frac{Q}{m_f} = h_4 - h_3 + \frac{m_s}{m_f}\left(h_{s4} - h_{s3}\right) + \frac{v_4^2 - v_3^2}{2gJ} + \frac{m_s}{m_f}\left[\frac{v_{s4}^2 - v_{s3}^2}{2gJ}\right] \tag{17}$$

The enthalpy of the solids (h_s) is given by (22):

$$h_T - h_{298.16} = 19.77\,T + 0.546 \times 10^{-3}\,T^2 + 4.86 \times 10^5\,T^{-1} - 7513$$

where T is expressed in $^{\circ}$K and h is expressed in gm-cal/mole. It can be shown that the change in enthalpy of the UO_2 is given by:

$$h_{s4}-h_{s3} = (T_4 - T_3)\left[19.77 + 0.546\times10^{-3}(T_4+T_3) - \frac{4.68\times10^5}{T_4T_3}\right]\frac{1.8}{270} \qquad (18)$$

where h is now expressed in Btu/lb.

Substitution into Equation 18 yields

$$h_{s4}-h_{s3} = \frac{1.8}{270}(824-594)\left[19.77+0.546\times10^{-3}(824+594) - \frac{4.68\times10^5}{(824)(594)}\right]$$

$$= 30 \text{ Btu/lb solid}$$

Calculations indicated that the contribution of the velocity terms in Equation 17 was negligible. Substitution into Equation 17 gives

$$\frac{1.66\times10^9}{m_{f4}} = 1502 - 1158.6 + 7.3(30)$$

$$m_{f4} = 2,945,000 \text{ lb/hr.}$$

$$m_{s4} = 21,450,000 \text{ lb/hr.}$$

Referring to Figure 8

$$m_{f4} = m_{f13} + m_{f12}$$

$$m_{f13} \cong m_{f5} = 1,372,000 \text{ lb/hr}$$

$$m_{f12} = m_{f4} - m_{f13} = (2.945 - 1.372)10^6 = 1,573,000 \text{ lb/hr}$$

$$m_{s12} = \left(\frac{m_s}{m_f}\right)_4 m_{f12} = 7.3(1,573,000) = 11,500,000 \text{ lb/hr}$$

$$m_{s11} = m_{s4}$$

$$m_{f11} \cong m_{f12}$$

$$\left(\frac{m_f}{m_s}\right)_{11} = \frac{1.573}{21.45} = 0.0732$$

$$e_{v11} = \frac{1}{1+\frac{m_{f11}\,\rho_s}{m_{s11}\,\rho_f}} = 0.0374$$

$$e_{s11} = \frac{1}{1 + \left(\frac{m_f}{m_s}\right)_{11}} = 0.931$$

Thus, it is seen that the solid volume and weight concentrations in the reheaters are 3.74 and 93.1 per cent, respectively. The per cent mixture recycled is

$$\frac{m_{12}}{m_4}(100) = \frac{11.5\,(100)}{21.45} = 53.5 \text{ per cent}$$

The pressure at point 11 must be lower than the pressure in the cyclone separators and therefore, a throttling orfice must be placed in line 12. Selection of the necessary pressure drop is difficult without actual design of the separators; however, a value of 50 psi was assumed. Therefore, the pressure at point 11 is 1550 psia.

D. Heat Balance of Reheater

Since the solid and vapor were considered separately in the heat balance, a trial and error solution was required to determine the conditions at the reheater. The following assumptions were made: the pressure drop on the slurry side of the reheater is 25 psi, the pressure drop on the steam side of the reheater is 6 psi, there is zero heat loss from the reheater, and the effect of the change in velocity of the slurry is negligible.

The temperature at point 9 can be calculated from the specified enthalpy change of the steam in the reheat portion of the cycle. The conditions now specified are

$P_{11} = 1550$ psia, $t_{11} = 1025^\circ$ F
$P_8 = 1525$ psia
$P_{10} = 430$ psia, $t_{10} = 1000^\circ$ F
$P_9 = 436$ psia, $t_9 = 699^\circ$ F
$m_{f11} = m_{f8} = 1{,}573{,}000$ lb/hr
$m_{s11} = m_{s8} = 21{,}450{,}000$ lb/hr
$m_{f9} = m_{f10} = 1{,}266{,}000$ lb/hr

The temperature at point 8 is the unknown to be solved for. A heat balance yields

$$m_s(h_{s_{11}} - h_{s_8}) + m_{f_{11}}(h_{11} - h_8) = m_{f9}(h_{10} - h_9) \qquad (19)$$

The change in enthalpy of the solid is given by Equation 18 with subscripts 4 and 3 replaced by subscripts 11 and 8, respectively. Solving equations 18 and 19 by trial and error gives a value of 945° F for t_8.

E. Size of Reheater

Utilizing the assumed and calculated conditions at the outlets and inlets to the reheater, an approximation of the area required for the reheater was calculated.

The area required is given by the equation

$$A_i = \frac{Q}{U_i \Delta t_m} \qquad (20)$$

The following equations apply

$$Q = (h_{10} - h_9)\, m_{10} \tag{21}$$

$$U_i = \frac{1}{\frac{1}{h_{ci}} + \frac{D_i}{2 k_t} \ln\left(\frac{D_o}{D_i}\right) + \frac{D_i}{D_o h_{co}}} \tag{22}$$

$$\Delta t_m = \frac{(t_8 - t_9) - (t_{11} - t_{10})}{\ln\left(\frac{t_8 - t_9}{t_{11} - t_{10}}\right)} \tag{23}$$

It was assumed that the reheaters consist of a heterogeneous array of tubes which are finned on the outside. The slurry was assumed to flow inside the tubes and the reheat steam outside the tubes. It was also assumed that Equation 21 was valid with the effect of the fins taken into account by an increase in h_o. It was assumed that D_i equals 1 in, that D_o equals 1.0625 in, and that the tubes in the heat exchanger are stainless steel. The steam was assumed to flow normal to the finned tubes and h_o was assumed to be 500 Btu/hr-ft^2-$^\circ$ F. The velocity of the slurry inside the tubes was assumed to be 30 fps.

The solution to equations 20 through 23 is as follows:

$$Q = 161.7(1{,}226{,}000) = 1.98 \times 10^8 \text{ Btu/hr}$$

$$\Delta t_m = \frac{(945 - 699) - (1025 - 1000)}{\ln\left(\frac{945 - 699}{1025 - 1000}\right)}$$

$$= 96.6\ ^\circ\text{F}$$

The average temperature of the slurry is 985° F and thus, the fluid properties at the average conditions from Reference 93 are

$$\mu = 7.5 \times 10^{-7} \ \text{lb-sec/ft}^2$$

$$\rho = 1.91 \ \text{lb/ft}^3$$

$$k = 0.0364 \ \text{Btu/hr-ft}^2\text{-}^{\circ}\text{F/ft}$$

$$c_p = 0.56 \ \text{Btu/lb-}^{\circ}\text{F}$$

The properties of the solid (UO_2) from Reference 87 are

$$k_s = 2.75 \ \text{Btu/hr-ft}^2\text{-}^{\circ}\text{F/ft}$$

$$c_{ps} = \frac{1}{270}\left(19.77 + 1.092 \times 10^{-3}\, T - 4.68 \times 10^{5}\, T^{-2}\right)$$

$$= 0.0738 \ \text{Btu/lb-}^{\circ}\text{F}$$

The density of the mixture from Equation 12 is

$$\rho_m = \frac{1 + 13.68}{\frac{1}{1.91} + \frac{13.68}{683}}$$

$$= 27 \ \text{lb/ft}^3$$

The thermal conductivity of the slurry is given by Equation 3

$$k_m = 0.0364 \left[\frac{2(0.0364) + 2.75 - 2(0.0374)(0.0364 - 2.75)}{2(0.0364) + 2.75 + 0.0374(0.0364 - 2.75)} \right]$$

$$= 0.0405 \ \text{Btu/hr-ft}^2\text{-}^{\circ}\text{F/ft}$$

The viscosity of the slurry is given by Equation 5

$$\mu_m = \frac{7.5 \times 10^{-7}}{1 - (0.0374)^{1/3}}$$

$$= 1.13 \times 10^{-6} \ \text{lb-sec/ft}^2$$

The specific heat of the mixture can be calculated by the following relation:

$$c_{pm} = \frac{1}{m_m}\left(m_s\, c_{ps} + m_f\, c_p\right)$$

$$= \frac{1}{23.02}\left[21.45(0.0738) + 1.573\,(0.56)\right]$$

$$= 0.45 \text{ Btu/lb-}^{\circ}\text{F}$$

The heat transfer coefficient for the slurry (h_i) is given by Equation 6

$$\frac{h_{e,i}\, D_i}{k_m} = 0.023\left(\frac{\rho_m v_m D_i}{\mu_m}\right)^{0.8}\left(\frac{c_{pm}\,\mu_m}{k_m}\right)^{0.4}$$

$$\frac{\rho_m v_m D_i}{\mu_m} = \frac{27\,(30)\,(1)}{(32.2)(1.13)(10^{-6})\,12} = 1,850,000$$

$$\frac{c_{pm}\,\mu_m}{k_m} = \frac{0.452\,(1.13)(10^{-6})(32.2)(3600)}{0.0405} = 1.46$$

$$h_{ei} = 1,350 \text{ Btu/hr-ft}^2\text{-}^{\circ}\text{F}$$

Substitution in Equation 22 yields

$$U_i = \frac{1}{\frac{1}{1350} + \frac{1.0}{12(2)8.4}\ln\left(\frac{1.0625}{1.0}\right) + \frac{1.0}{1.0625(500)}}$$

$$= 342 \text{ Btu/hr-ft}^2\text{-}^{\circ}\text{F}$$

Therefore, from Equation 20, the average effective area needed for the reheaters is

$$A_i = \frac{Q}{U_i\,\Delta t_m} = \frac{1.98\times10^{8}}{342\,(96.6)} = 6000 \text{ ft}^2$$

The pumping power required for the high pressure feed pumps with the assumed inlet and discharge pressures of 20 and 1775 psi may be estimated as follows:

$$PHP = \frac{\Delta P \, m_{f2}}{\rho_{f2}} = \frac{(1775 - 20)(144)(1,372,000)}{51.7\,(3600)(550)}$$

$$= 3400 \text{ hp}$$

$$= 2530 \text{ kw}$$

X. APPENDIX C. CRITICALITY ANALYSIS OF VAPOR SLURRY REACTOR

The criticality analysis was conducted in order to obtain an approximate picture of the nuclear aspects of the Vapor Slurry Reactor. A summary of the results of the analysis is presented in Figure 7 in the text of the report.

The Fermi Age treatment was used for evaluation of reactor criticality and U^{235} was assumed to be the fissionable component of the uranium dioxide slurry particles. It was assumed that the critical equation for a large reactor was valid, where (94)

$$B_m^2 = \frac{k_\infty - 1}{M^2} = \frac{k_\infty - 1}{L^2 + \tau} \qquad (24)$$

For a cylindrical reactor

$$B_m^2 = \left(\frac{\pi}{H}\right)^2 + \left(\frac{2.405}{R}\right)^2 \qquad (25)$$

For minimum volume of a cylindrical reactor $H = 1.847\ R$. Substitution of this into Equation 25 yields

$$B_m^2 = \frac{8.674}{R^2} \qquad (26)$$

Substitution of Equation 26 into Equation 24 gives

$$R^2 = \frac{8.674(L^2 + \tau)}{k_\infty - 1} \qquad (27)$$

Evaluation of the unknown parameters of Equation 27 must then be undertaken.

A. Evaluation of Infinite Multiplication Factor

The infinite multiplication factor (k_∞) is given by the four-factor formula

$$k_\infty = \eta \epsilon f p$$

The fast fission factor (ϵ) was assumed to be constant and equal to 1.03. The other factors composing k_∞ were evaluated as follows:

$$\eta = \frac{\nu \Sigma_f}{\Sigma_{fuel}} = \frac{\nu N_{U5} \bar{\sigma}_{f,U5}}{N_{U8} \bar{\sigma}_{a,U8} + N_{U5} \bar{\sigma}_{a,U5}}$$

$$f = \frac{\Sigma_{a,fuel}}{\Sigma_{a,total}} = \frac{N_{U8} \bar{\sigma}_{a,U8} + N_{U5} \bar{\sigma}_{a,U5}}{N_{U8} \bar{\sigma}_{a,U8} + N_{U5} \bar{\sigma}_{a,U5} + N_{H_2O} \bar{\sigma}_{a,H_2O} + N_{BeO} \bar{\sigma}_{a,BeO} + N_t \bar{\sigma}_{a,t}}$$

$$\eta \epsilon f = \frac{\epsilon \nu N_{U5} \bar{\sigma}_{f,U5}}{N_{U8} \bar{\sigma}_{a,U8} + N_{U5} \bar{\sigma}_{a,U5} + N_{H_2O} \bar{\sigma}_{a,H_2O} + N_{BeO} \bar{\sigma}_{a,BeO} + N_t \bar{\sigma}_{a,t}}$$

$$= \frac{\epsilon \nu \bar{\sigma}_{f,U5}}{\frac{N_{U8}}{N_{U5}} \bar{\sigma}_{a,U8} + \bar{\sigma}_{a,U5} + \frac{N_{H_2O}}{N_{U5}} \bar{\sigma}_{a,H_2O} + \frac{N_{BeO}}{N_{U5}} \bar{\sigma}_{a,BeO} + \frac{N_t}{N_{U5}} \bar{\sigma}_{a,t}}$$

$$p = \exp\left[- \frac{N_{U8}}{\xi \Sigma_{s,total}} \int \bar{\sigma}_{a,eff} \frac{dE}{E} \right]$$

$$= \exp\left[- \frac{N_{U8} \int \bar{\sigma}_{a,eff} \frac{dE}{E}}{\xi_{H_2O} N_{H_2O} \bar{\sigma}_{s,H_2O} + \xi_{BeO} N_{BeO} \bar{\sigma}_{s,BeO} + (\xi_O N_O \bar{\sigma}_{s,O})_{UO_2}} \right]$$

$$P = \exp\left[- \frac{\int \sigma_{a\,eff} \frac{dE}{E}}{\xi_{H_2O}\,\sigma_{s,H_2O}\left(\frac{N_{H_2O}}{N_{U8}}\right) + \xi_{BeO}\,\sigma_{s,BeO}\left(\frac{N_{BeO}}{N_{U8}}\right) + \xi_{O}\,\sigma_{s,O}\left(\frac{N_O}{N_{U8}}\right)} \right]$$

It has been shown that $\int \sigma_{a\,eff} \frac{dE}{E}$ is a function of Σ_s total/N_{U8} (94, p. 256)

$$\int \sigma_{a\,eff} \frac{dE}{E} = 3.87\left(\frac{\Sigma_{s,\,total}}{N_{U8}}\right)^{0.415} \tag{28}$$

Equation 28 is valid when Σ_s total/N_{U8} is less than 1000. When values of Σ_s total/N_{U8} are greater than 1000, $\int \sigma_{a\,eff} \frac{dE}{E}$ may be obtained from Figure 9.

In order to account for the different volumes of the reactor components, the atom or molecule densities (N) were expressed in atoms or molecules per cm^3 of reactor. Thus, the following equations apply:

$$N_{UO_2} = N_U = N_{U5} + N_{U8} \qquad \left(\frac{N_O}{N_{UO_2}}\right)_{UO_2} = 2$$

$$N_{H_2O} = (N_{U5} + N_{U8})\,\frac{N_{H_2O}}{N_{UO_2}}$$

$$\frac{N_{H_2O}}{N_{U5}} = \left(1 + \frac{N_{U8}}{N_{U5}}\right)\frac{N_{H_2O}}{N_{UO_2}}$$

$$\frac{N_{H_2O}}{N_{UO_2}} = \frac{A_{UO_2}}{A_{H_2O}}\left(\frac{m_{H_2O}}{m_{UO_2}}\right) = \frac{A_{UO_2}}{A_{H_2O}}\left(\frac{\rho_{H_2O}}{\rho_{UO_2}}\right)\left(\frac{1}{e_v} - 1\right)$$

$$\frac{N_t}{N_{UO_2}} = \frac{N_{x,t}}{N_{x,UO_2}}\left(\frac{V_t}{V_{UO_2}}\right)$$

$$\frac{V_t}{V_{UO_2}} \cong \frac{\pi D t}{e_v\,\pi D^2/4} = \frac{4t}{e_v D}$$

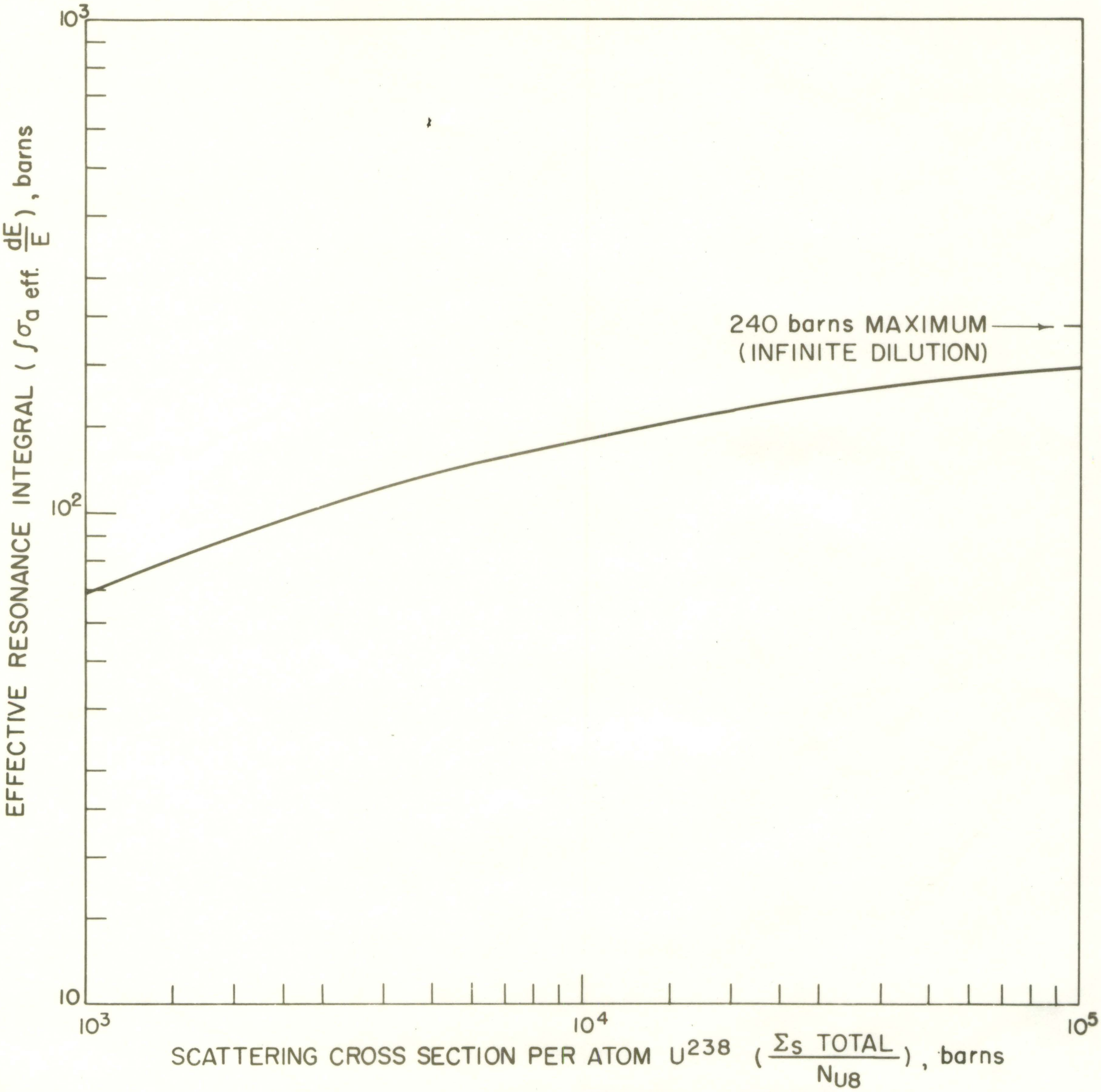

FIGURE 9 EFFECTIVE RESONANCE INTEGRAL

Then equations from which k_∞ can be calculated reduce to

$$\eta \epsilon f = \frac{\epsilon \nu \sigma_{f,U5}}{\sigma_{a,U5} + \frac{N_{U8}}{N_{U5}}\left[\sigma_{a,U8} + \frac{N_{H_2O}}{N_{UO_2}} \sigma_{a,H_2O} + \frac{\Sigma_{a,t}}{N_{UO_2}}\right] + \frac{N_{H_2O}}{N_{UO_2}} \sigma_{a,H_2O} + \frac{\Sigma_{a,t}}{N_{UO_2}} + \frac{N_{BeO}}{N_{U5}} \sigma_{a,BeO}} \tag{29}$$

$$P = \exp\left[- \frac{\int \sigma_{a,eff} \frac{dE}{E}}{\left(1 + \frac{N_{U5}}{N_{U8}}\right)\left[\xi_{H_2O} \sigma_{s,H_2O} \frac{N_{H_2O}}{N_{UO_2}} + 2 \xi_O \sigma_{s,O}\right] + \xi_{BeO} \sigma_{s,BeO} \frac{N_{BeO}}{N_{U8}}}\right] \tag{30}$$

$$\int \sigma_{a,eff} \frac{dE}{E} = 3.87 \left(\frac{\Sigma_{s,total}}{N_{U8}}\right)^{0.415} \qquad \frac{\Sigma_{s,total}}{N_{U8}} < 1000 \tag{28}$$

$$\frac{\Sigma_{s,total}}{N_{U8}} = \sigma_{s,U8} + \left(1 + \frac{N_{U8}}{N_{U5}}\right)\left[\frac{N_{H_2O}}{N_{UO_2}} \sigma_{s,H_2O} + 2 \sigma_{s,O}\right] + \frac{N_{BeO}}{N_{U8}} \sigma_{s,BeO} \tag{31}$$

$$\frac{N_{H_2O}}{N_{UO_2}} = \left(\frac{1}{e_v} - 1\right)\left(\frac{\rho_{H_2O}}{\rho_{UO_2}}\right)\left(\frac{A_{UO_2}}{A_{H_2O}}\right) \tag{32}$$

$$\frac{\Sigma_{a,t}}{N_{UO_2}} = \frac{4 t \Sigma_{a,t} 10^{24}}{N_{x,UO_2} e_v D} \tag{33}$$

Constants for the preceding equations were evaluated on the basis of an average reactor temperature of 840° F (722° K). The neutron cross sections used for calculating η and f must be thermal values while those used for calculating p must be epithermal.

The thermal absorption cross sections were assumed to vary as 1/v and to have a Maxwell distribution. The energy of thermal neutrons at the average reactor temperature is given by

$$\text{Energy of thermal neutrons} = 8.61 \times 10^{-5}\ T$$

$$= 8.61 \times 10^{-5}\ (722)$$

$$= 0.0621 \text{ ev}$$

The thermal absorption cross sections of H_2O, BeO, and stainless steel were calculated from tabular data and the following relation, which is based on the 1/v law:

$$\sigma_a = \sigma_{a_0}\left(\frac{T_0}{T}\right)^{1/2} = \sigma_{a_0}\left(\frac{298}{722}\right)^{1/2} \qquad (34)$$

$$= 0.642\ \sigma_{a_0}$$

The subscript o refers to values at 0.025 ev. The other thermal cross sections were taken from cross section curves at any energy equal to 0.0621 ev (96,97). The cross sections used to calculate k_∞ are listed in Table 5. A value of 0.253 cm^{-1} for the thermal macroscopic absorption cross section of type 347 stainless steel (Σ_{at}) was obtained from Murray (98 p. 176) and corrected for temperature by Equation 34. Thus, Σ_{at} = 0.162 cm^{-1} was used in the k_∞ calculations. The tube diameter and thickness were specified to be 1 in. and 1/32 in., respectively. Other constants which were required are listed in Table 6. The thickness of the 347 stainless steel tube is important because stainless steel is the primary neutron absorber in the reactor core. The stress in this tube will be

$$S = \frac{PD}{2t} = \frac{1650(1)(32)}{2} = 26{,}600 \text{ psi}$$

TABLE 5: CROSS SECTIONS USED TO CALCULATE k_∞

Cross Section	Neutron Energy	Value barns	Reference
σ_a, U5	0.0621 ev	442	98
σ_f, U5	0.0621 ev	352	98
σ_a, U8	0.0621 ev	2.75	98
σ_a, H_2O	0.0621 ev	0.424	95, p. 377
σ_a, BeO	0.0621 ev	0.0059	95, p. 377
σ_s, H_2O	epithermal	46	95, p. 377
σ_s, BeO	epithermal	9.8	95, p. 377
σ_s, O	epithermal	3.8	96

TABLE 6: REACTOR CONSTANTS

Material	A	ρ gm/cm^3	ξ
H_2O	18	0.0394	0.927
BeO	25	2.80	0.174
UO_2	270	10.96	——
O	16	——	0.120

The 0.2 per cent offset yield strength of 347 stainless steel at 1000° F is approximately 31,000 psi. In order to achieve an appreciable factor of safety the BeO bricks will be required to provide some tube support. The coefficient of linear expansion of stainless steel is approximately 10.7×10^{-6} while that of BeO is approximately 9.3×10^{-6} and therefore, utilizing the BeO for support seems feasible. Gamma heating of the stainless steel tubes in the reactor may cause additional difficulty, due to a possible low heat transfer coefficient between the tubes and the vapor slurry.

It can be seen from Equations 28 through 33 that k_∞ can be expressed as a function of the following reactor variables:

$$k_\infty = \phi\left(\frac{N_{U5}}{N_{U8}}, e_v, \frac{N_{BeO}}{N_{U5}}\right) \tag{35}$$

If two of these variables are held fixed, k_∞ can be plotted versus the other. Such plots are shown in Figures 10 and 11 which summarize the calculations of the infinite multiplication factor.

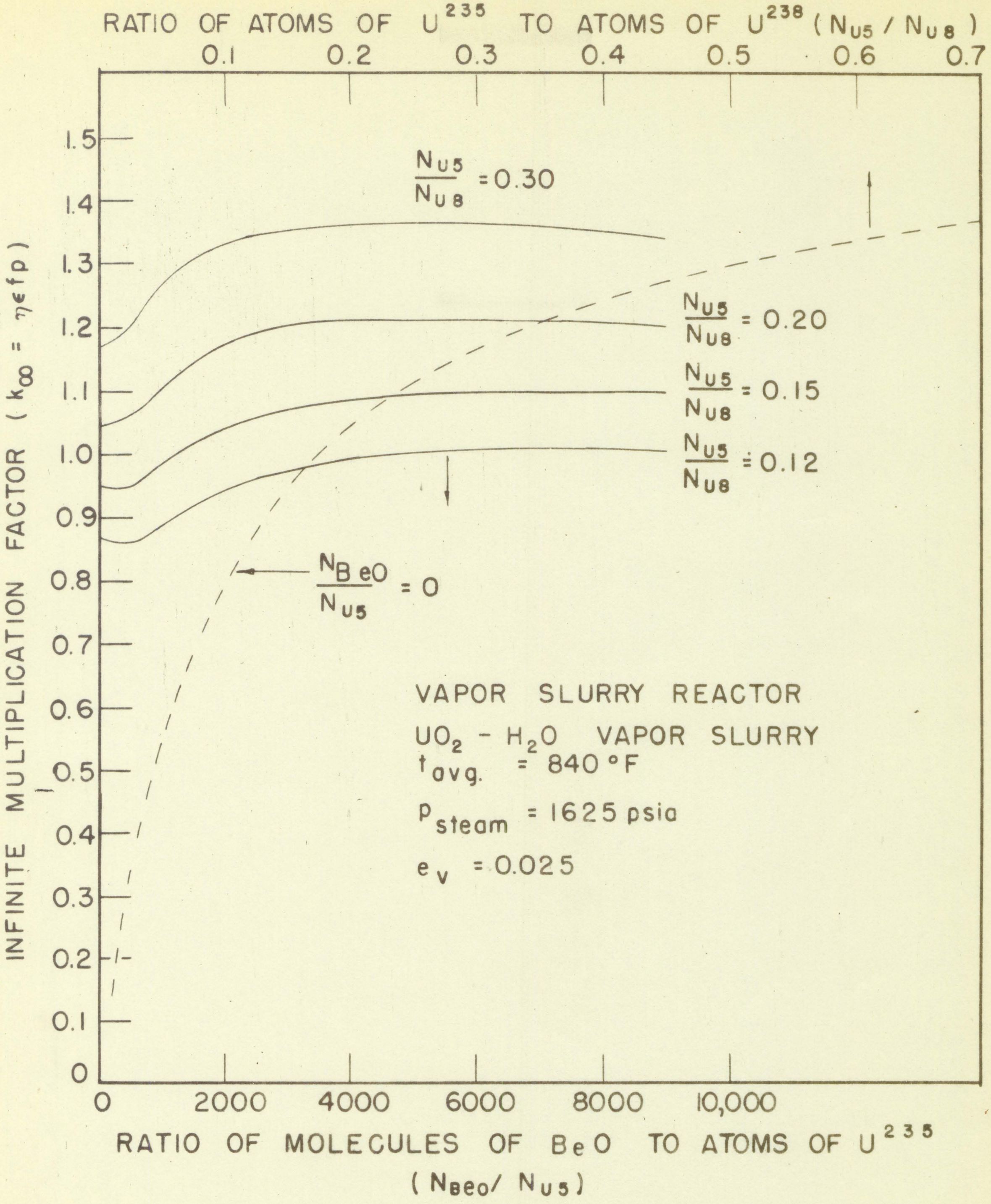

FIGURE 10. INFINITE MULTIPLICATION FACTOR VERSUS REACTOR VARIABLES WITH FIXED VOLUME CONCENTRATION

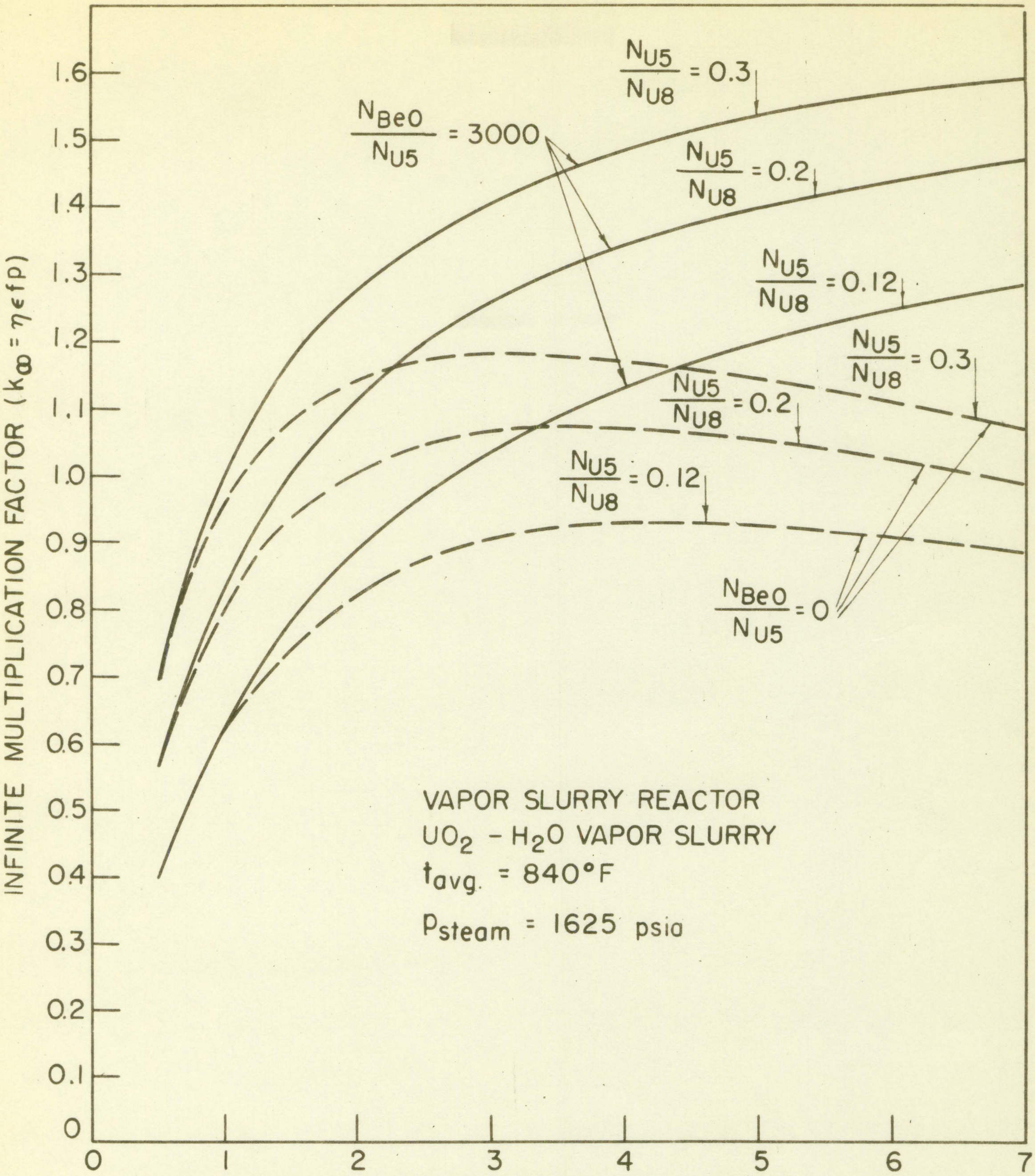

FIGURE II INFINITE MULTIPLICATION FACTOR VERSUS VOLUME SOLIDS CONCENTRATION OF SLURRY

B. Evaluation of Thermal Diffusion Length

If it is assumed that the system is a weak absorber, the square of the thermal diffusion length is given by the following relation:

$$L^2 = \frac{1}{3 \Sigma_a \Sigma_{tr}} \qquad (36)$$

where: $$\Sigma_a = \Sigma_{a,H_2O} + \Sigma_{a,BeO} + \Sigma_{a,t} + \Sigma_{a,UO_2} \qquad (37)$$

$$\Sigma_{tr} = \Sigma_{tr,H_2O} + \Sigma_{tr,BeO} + \Sigma_{tr,t} + \Sigma_{tr,UO_2} \qquad (38)$$

The effects of U and stainless steel on Σ_{tr} and the effect of the oxygen in UO_2 on Σ_a were neglected. The thermal transport cross sections are given by:

$$\sigma_{tr} = \sigma_s (1 - \overline{\cos \theta})$$

$$\sigma_{tr,Be} = 5.9(0.9257) = 5.46 \text{ b}$$

$$\sigma_{tr,O} = 3.9(0.9583) = 3.74 \text{ b}$$

where σ_s is the scattering cross section determined from cross section curves at the assumed thermal neutron energy of 0.0621 ev. The effect of the chemical binding of the hydrogen atom to the water molecule significantly alters the hydrogen atoms thermal scattering properties. The method of Bogart and Soffer (70) which defines an effective thermal transport cross section for hydrogen ($\overline{\sigma}_{tr,H}$) was used to account for this effect. The effective thermal transport cross section for hydrogen was found to be 21 b at the average reactor temperature of 840° F (70, p. 38).

Because the thermal parameters which express k_∞ represent ratios of cross sections, the thermal absorption cross sections used in calculating k_∞ did not require averaging over their Maxwell distribution. In evaluating L^2 the effect of the Maxwell distribution of thermal neutrons must be taken into consideration. The average thermal neutron speed is 1.128 times greater than the most probable speed and therefore, the effective thermal absorption cross sections (σ_a') are 0.866 times the cross sections corresponding to the thermal neutron energy. Thus, the absorption cross sections which were used in Equation 37 and 38 were obtained by multiplying the thermal absorption cross sections listed in Table 5 by 0.866. Expansion of Equations 37 and 38 and substitution of the specified cross sections, gives

$$\frac{\Sigma_{tr}}{N_{UO_2}} = \frac{N_{H_2O}}{N_{UO_2}}\left(2\sigma_{tr,H} + \sigma_{tr,O}\right) + \frac{N_{BeO}}{N_{UO_2}}\left(\sigma_{tr,Be} + \sigma_{tr,O}\right) + 2\sigma_{tr,O}$$

$$\frac{\Sigma_{tr}(10^{24})}{N_{UO_2}} = \frac{N_{H_2O}}{N_{UO_2}}\left[2(21) + 3.74\right] + \frac{N_{BeO}}{N_{UO_2}}\left(5.46 + 3.74\right) + 2(3.74)$$

$$= 45.74\,\frac{N_{H_2O}}{N_{UO_2}} + 9.10\,\frac{N_{BeO}}{N_{UO_2}} + 7.48$$

$$\frac{(\Sigma_a')10^{24}}{N_{UO_2}} = \frac{N_{H_2O}}{N_{UO_2}}\,\sigma_{a,H_2O}' + \frac{N_{BeO}}{N_{UO_2}}\,\sigma_{a,BeO}' + \frac{N_{U5}}{N_{UO_2}}\,\sigma_{a}'{}_{U5} + \frac{N_{U8}}{N_{UO_2}}\,\sigma_{a}'{}_{U8}$$

$$= 3.76\,\frac{N_{H_2O}}{N_{UO_2}} + 0.00523\,\frac{N_{BeO}}{N_{UO_2}} + 382\,\frac{N_{U5}}{N_{UO_2}} + 2.44\,\frac{N_{U8}}{N_{UO_2}}$$

Simplification gives

$$\frac{\Sigma_{tr}}{N_{UO_2}} = \left[\frac{2.47}{e_v} + \frac{N_{BeO}}{N_{U5}}\left(\frac{9.10}{1+\frac{N_{U8}}{N_{U5}}}\right) + 5.01\right]10^{-24} \tag{39}$$

$$\frac{\Sigma_a'}{N_{UO_2}} = 10^{-24}\left[\frac{0.7563}{e_v} + \frac{N_{BeO}}{N_{U5}}\left(\frac{0.00523}{1+\frac{N_{U8}}{N_{U5}}}\right) + \frac{382}{\left(1+\frac{N_{U8}}{N_{U5}}\right)} + \frac{2.44}{1+\frac{N_{U5}}{N_{U8}}} - 0.0203\right] \tag{40}$$

The number of molecules per cubic centimeter of the uranium oxide in the reactor (N_{UO_2}) can be evaluated as follows:

$$N_{UO_2} = \left(\frac{\text{molecules } UO_2}{\text{cm}^3\ UO_2}\right)\left(\frac{\text{cm}^3\ UO_2}{\text{cm}^3 \text{ reactor}}\right) = N_{x,UO_2}\left(\frac{V_{UO_2}}{V_R}\right) \tag{41}$$

$$\frac{V_{UO_2}}{V_R} = \frac{V_{UO_2}}{V_{UO_2} + V_{BeO} + V_{H_2O} + V_t}$$

$$= \frac{1}{1 + \frac{V_{BeO}}{V_{UO_2}} + \frac{V_{H_2O}}{V_{UO_2}} + \frac{V_t}{V_{UO_2}}}$$

$$\frac{V_{H_2O}}{V_{UO_2}} = \frac{1}{e_v} - 1$$

$$\frac{V_{BeO}}{V_{UO_2}} = \frac{N_{BeO}}{N_{UO_2}}\left(\frac{N_{UO_2\,x}}{N_{x,BeO}}\right) = \frac{N_{BeO}}{N_{UO_2}}\left(\frac{A_{BeO}}{A_{UO_2}}\right)\left(\frac{\rho_{UO_2}}{\rho_{BeO}}\right)$$

$$\frac{N_{BeO}}{N_{UO_2}} = \frac{N_{BeO}}{N_{U5}}\left(\frac{1}{1+\frac{N_{U8}}{N_{U5}}}\right)$$

$$\frac{V_t}{V_{UO_2}} = \frac{4\,t}{e_v\,D}$$

Substituting the previously specified values for the reactor parameters into the preceding five equations and in turn substituting these equations into Equation 41, yields

$$N_{UO_2} = \frac{2.445 \times 10^{22}}{\frac{1.08}{e_v} + 0.3626\,\frac{N_{BeO}}{N_{U5}}\left[\frac{1}{1+\frac{N_{U8}}{N_{U5}}}\right]} \qquad (42)$$

Equation 36 can be written

$$\frac{1}{L^2} = 3\,N_{UO_2}^2\left(\frac{\Sigma_a'}{N_{UO_2}}\right)\left(\frac{\Sigma_{tr}}{N_{UO_2}}\right) \qquad (43)$$

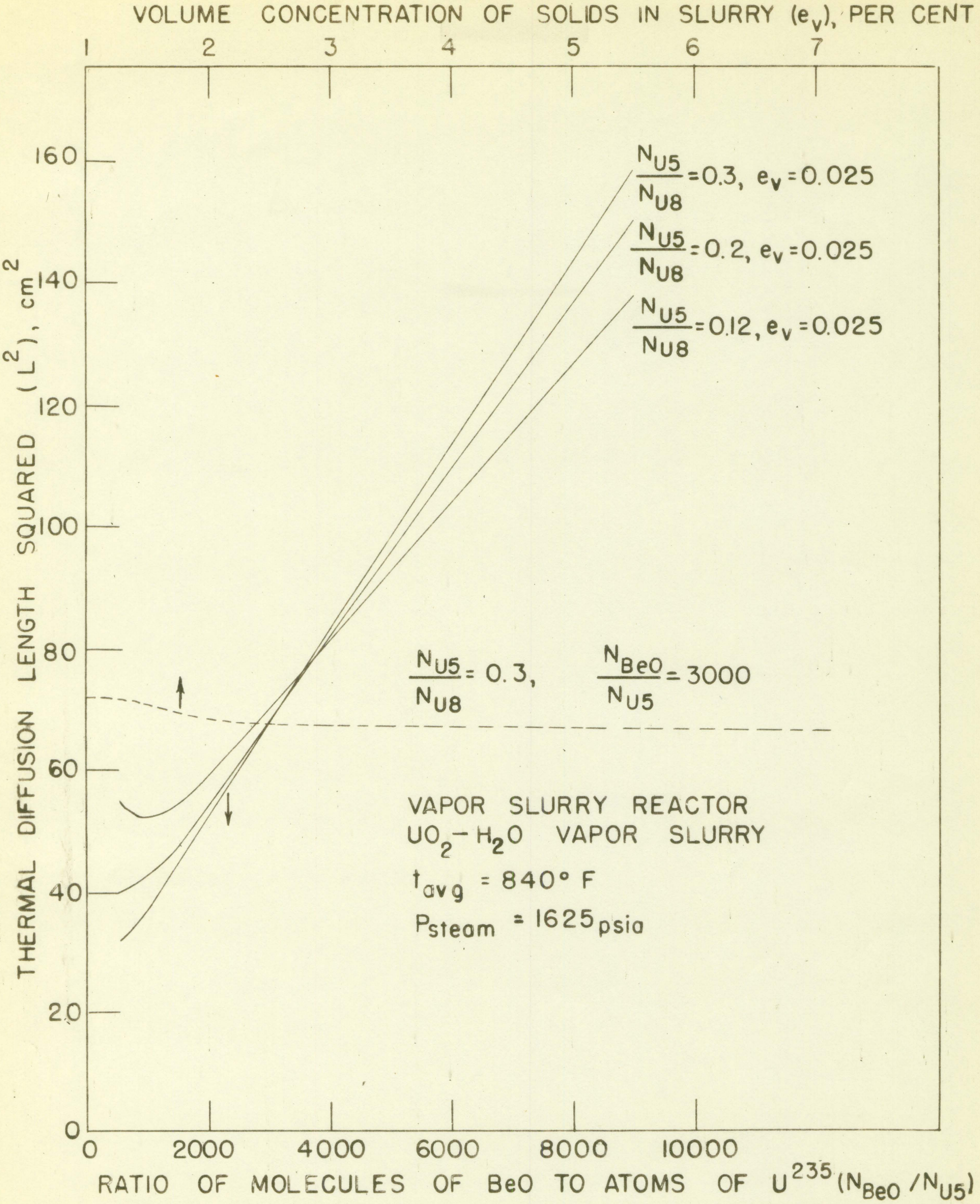

FIGURE 12. THERMAL DIFFUSION LENGTH VERSUS REACTOR VARIABLES

The thermal diffusion length was calculated for varying reactor variables using Equation 39, 40, 42, and 43. The results of this calculation are presented in Figure 12.

C. Evaluation of Fermi Age

A rigorous evaluation of the slowing down length in a system of two moderators is quite complicated (88,89) and did not seem warranted for this preliminary analysis. Simplicity and reasonable accuracy can be obtained from the Fermi Age treatment if certain modifications are applied to the constants involved in the calculations.

The Fermi Age or the square of the mean slowing down length is given by the following relation:

$$\tau = L_s^2 = \int_{E_{th}}^{E} \frac{\lambda_{tr}}{3 \xi \Sigma_s} \frac{dE}{E} \tag{44}$$

If it is assumed that all neutrons originate at an average fission energy (E_{avg}) and that the other factors in the above equation are independent of energy, then the relation for age can be integrated with the following results:

$$\tau = \frac{1}{3 \xi \Sigma_s \Sigma_{tr}} \ln \frac{E_{avg}}{E_{th}} \tag{45}$$

It has been shown that the average fission energy of neutrons originating from U^{235} equals 2 Mev (99). Thus, for the assumed temperature of the Vapor Slurry Reactor

$$\tau = \frac{1}{3\xi\Sigma_s\Sigma_{tr}} \ln\left(\frac{2\times10^6}{0.0621}\right) = \frac{5.76}{\xi\Sigma_s\Sigma_{tr}} \tag{46}$$

The components of this equation are given by

$$\xi\Sigma_s = \xi_{BeO}\Sigma_{s,BeO} + \xi_{H_2O}\Sigma_{s,H_2O} + \xi_{UO_2}\Sigma_{s,UO_2} + \xi_t\Sigma_{s,t}$$

$$\Sigma_{tr} = \Sigma_{tr,BeO} + \Sigma_{tr,H_2O} + \Sigma_{tr,UO_2} + \Sigma_{tr,t}$$

The effects of scattering by stainless steel and uranium were neglected, thus

$$\xi\Sigma_s = N_{BeO}(\xi_{Be}\sigma_{s,Be} + \xi_O\sigma_{s,O}) + N_{H_2O}(2\xi_H\sigma_{s,H} + \xi_O\sigma_{s,O}) + 2N_{UO_2}\xi_O\sigma_{s,O} \tag{47}$$

$$\Sigma_{tr} = N_{BeO}\left[\sigma_{tr,Be} + \sigma_{tr,O}\right] + N_{H_2O}\left[2\sigma_{tr,H} + \sigma_{tr,O}\right] + 2N_{UO_2}\sigma_{tr,O}$$

$$\Sigma_{tr} = N_{BeO}\left[\sigma_{s,Be}W_{Be} + \sigma_{s,O}W_O\right] + N_{H_2O}\left[2\sigma_{s,H}W_H + \sigma_{s,O}W_O\right] + 2N_{UO_2}\sigma_{s,O}W_O \tag{48}$$

All cross sections used in the preceding equations must be epithermal. The previous assumption that $\xi\Sigma_s$ is independent of energy is not valid and therefore, epithermal cross sections which will provide an accurate result for the Fermi Age are not available. In order to alleviate this difficulty effective epithermal scattering cross sections ($\bar{\sigma}_s$) were defined for beryllium and hydrogen. These effective values were calculated by assuming that Equation 45 was valid and calculating an effective cross section from experimentally determined values of the Fermi Age. The following data were available from the literature (95):

$$\tau_{Be}\,(0.025\text{ ev}) = 98 \qquad \rho = 1.84$$

$$\tau_{H_2O}\,(0.025\text{ ev}) = 33 \qquad \rho = 1.0$$

It was assumed that the effective epithermal scattering cross section of oxygen is 3.5 b. For H_2O, using Equation 45

$$\tau_{H_2O} = 33 = \frac{1}{3\xi\Sigma_s\Sigma_{tr}} \ln\left(\frac{2\times10^6}{0.025}\right) = \frac{6.06}{\xi\Sigma_s\,\Sigma_{tr}}$$

$$\xi\Sigma_s = N_{H_2O}\left[\xi_O\,\bar{\sigma}_{s,O} + 2\,\xi_H\,\bar{\sigma}_{s,H}\right]$$

$$= 3.35\times10^{22}\left[0.120(3.5) + 2(1.0)\,\bar{\sigma}_{s,H}\right]10^{-24}$$

$$\Sigma_{tr} = N_{H_2O}\left[\bar{\sigma}_{s,O}\,W_O + 2\,\bar{\sigma}_{s,H}\,W_H\right]$$

$$= 3.35\times10^{22}\left[3.5(0.9583) + 2(0.333)\,\bar{\sigma}_{s,H}\right]10^{-24}$$

$$\frac{6.06}{33} = (0.0335)^2(0.42 + 2\bar{\sigma}_{s,H})(3.355 + 0.666\,\bar{\sigma}_{s,H})$$

$$\bar{\sigma}_{s,H} = 8.75\text{ b}$$

For Be

$$\tau_{Be} = 98 = \frac{6.06}{\xi \Sigma_s \Sigma_{tr}} = \frac{6.06}{\xi_{Be} \Sigma_{s,Be}^2 W_{Be}}$$

$$\Sigma_{s,Be}^2 = 0.32$$

$$\bar{\sigma}_{s,Be} = 4.59b$$

The validity of the above method was checked by calculating the Fermi Age for BeO and comparing it with experimental values. For BeO with a density of 3.0 gm/cm^3

$$(\xi \Sigma_s)_{BeO} = N_{BeO}\left(\xi_O \bar{\sigma}_{s,O} + \xi_{Be} \bar{\sigma}_{s,Be}\right)$$

$$= 7.23 \times 10^{22}\left[0.120(3.5) + 0.209(4.59)\right] 10^{-24}$$

$$= 0.0997$$

$$\Sigma_{tr,BeO} = N_{BeO}\left[\sigma_{s,O} W_O + \sigma_{s,Be} W_{Be}\right]$$

$$= 7.23 \times 10^{22}\left[3.5(0.9583) + 4.59(0.9257)\right]$$

$$= 0.549$$

$$\tau_{BeO}(0.025\,ev) = \frac{6.06}{\xi \Sigma_s \Sigma_{tr}} = \frac{6.06}{(0.0997)(0.549)}$$

$$= 110.8\ cm^2$$

Comparison of this value with an experimental value of 105 ± 10 cm^2 (100, p. 9) indicated that the method was reasonably accurate.

The Fermi Age in the reactor was calculated using $\bar{\sigma}_{s,H} = 8.75$ b, $\bar{\sigma}_{s,Be} = 4.59$ b, and $\bar{\sigma}_{s,O} = 3.5$ b. Substitution of these values into Equations 47 and 48 gave

$$\frac{\xi \Sigma_s}{N_{UO_2}} = \left[\frac{0.968}{e_v} + \frac{N_{BeO}}{N_{U5}} \left(\frac{1.38}{1 + \frac{N_{U5}}{N_{U8}}} \right) - 0.128 \right] 10^{-24} \qquad (49)$$

$$\frac{\Sigma_{tr}}{N_{UO_2}} = \left[\frac{0.496}{e_r} + \frac{N_{BeO}}{N_{U5}} \left(\frac{7.605}{1 + \frac{N_{U5}}{N_{U8}}} \right) + 6.214 \right] 10^{-24} \qquad (50)$$

Equation 46 can be written as

$$\tau = \frac{5.76}{N_{UO_2}^2 \left(\frac{\xi \Sigma_s}{N_{UO_2}} \right) \left(\frac{\Sigma_{tr}}{N_{UO_2}} \right)} \qquad (51)$$

Thus, Equation 42, 49, 50, and 51 can be used to calculate the Fermi Age in the reactor. The results of the calculations which were completed for this analysis are presented in Figure 13.

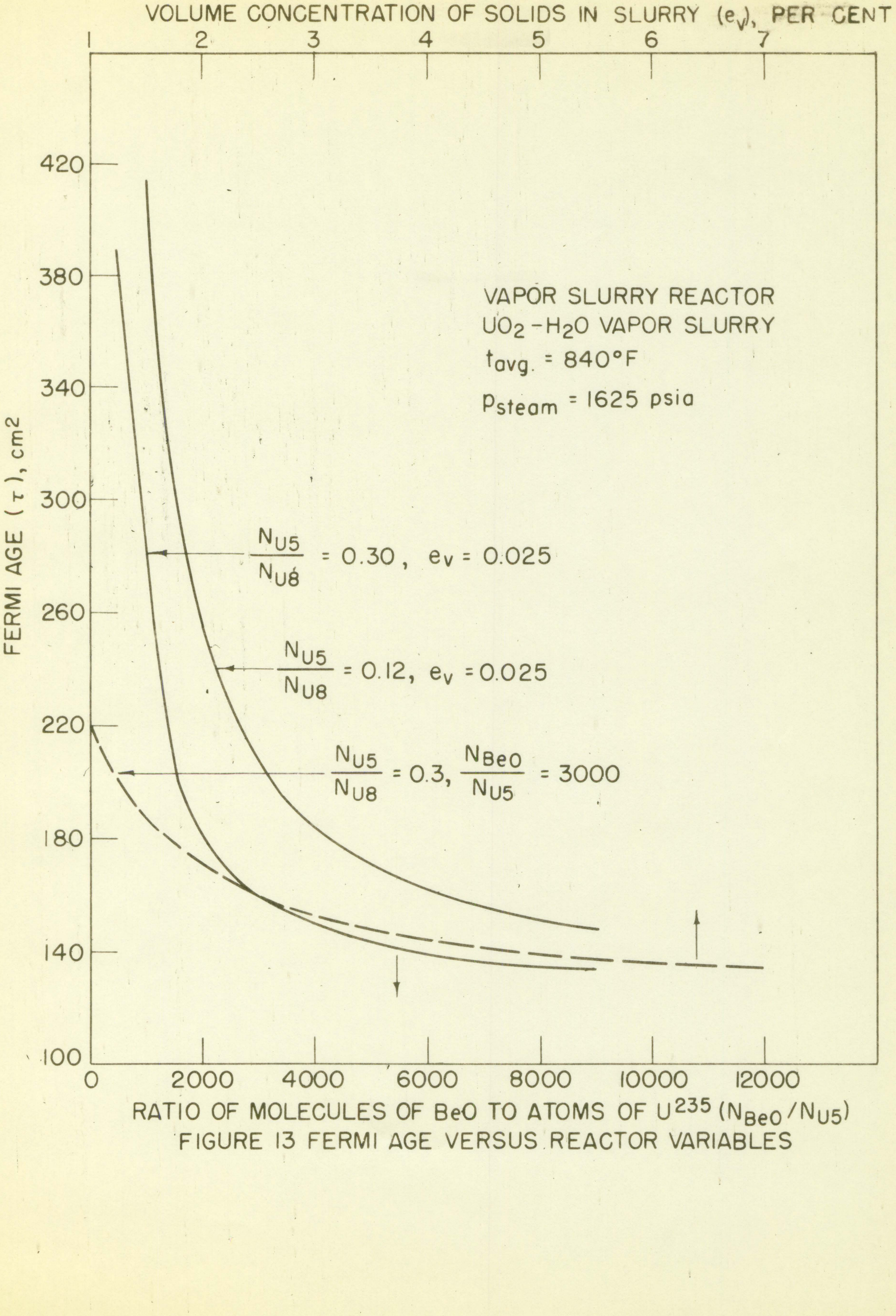

FIGURE 13 FERMI AGE VERSUS REACTOR VARIABLES

D. Other Preliminary Calculations

The previously specified tube diameter, slurry solids concentration, and slurry velocity fixed several of the reactor variables so that an arbitrary enrichment and moderator ratio could not be selected. It was assumed that an average area of the mixture ($\bar{A}_m$) would define the total axial flow area of the reactor. From the thermal analysis the mass rate of flow of the mixture equals 24,450,000 lb/hr and the average density and velocity of the slurry equal 19.4 lb/ft^3 and 73.3 fps, respectively. Thus

$$\bar{A}_m = \frac{m_m}{\bar{\rho}_m \bar{v}_m} = \frac{24,450,000}{19.4(73.3)(3600)}$$

$$= 4.78 \text{ ft}^2$$

From Equations 41 and 42

$$\frac{V_R}{V_{UO_2}} = \frac{N_{x,UO_2}}{N_{UO_2}} = \frac{1.08}{e_v} + 0.3626 \frac{N_{BeO}}{N_{U5}} \left(\frac{1}{1 + \frac{N_{U8}}{N_{U5}}} \right)$$

The volume concentration was specified to be 2.5 per cent. Thus

$$\frac{V_R}{V_{UO_2}} = 43.2 + 0.3626 \frac{N_{BeO}}{N_{U5}} \left(\frac{1}{1 + \frac{N_{U8}}{N_{U5}}} \right)$$

The following equations also apply:

$$V_R = \pi R_c^2 H = \pi R^2 (1.847 R) = 5.79 R^3$$

$$V_{UO_2} = e_v \bar{V}_m = e_v \bar{A}_m H = 0.025 (4.78)(1.847 R)$$

$$= 0.22 R$$

$$\frac{V_R}{V_{UO_2}} = 26.35\,R^2$$

Therefore

$$26.35R^2 = 43.2 + 0.3626\,\frac{N_{BeO}}{N_{U5}}\left(\frac{1}{1+\frac{N_{U8}}{N_{U5}}}\right) \tag{52}$$

Equation 52 was solved by trial and error with reference to Figure 7 and it was found that the following values satisfied all specified conditions:

$$R = 3.25 \text{ ft}$$

$$\frac{N_{BeO}}{N_{U5}} = 3860$$

$$\frac{N_{U5}}{N_{U8}} = 0.2$$

Thus: $H = 1.847\,(3.25) = 6 \text{ ft}$

$$\text{Enrichment} = \frac{100\,N_{U5}}{N_{U5}+N_{U8}} = \frac{100\,(0.2)}{0.2+1} = 16.67 \text{ per cent}$$

From the assumption concerning the area of the slurry, the approximate number of tubes required can be calculated

$$\text{No. tubes} \cong \frac{\bar{A}_m}{A} = \frac{4.78}{\pi D^2/4} = \frac{4(4.78)144}{3.14(1)}$$

$$= 877$$

The weight of UO_2 in the core at any instant is determined as follows:

$$V_{UO_2} = 0.22 R_c = 0.22(3.25) = 0.715 \text{ ft}^3$$

$$\text{Wt. } UO_2 = V_{UO_2} \rho_{UO_2} = 0.715(10.96)(62.4) = 489 \text{ lb}$$

$$= 222 \text{ kg}$$

The weight of U^{235} in the core at any instant is

$$\text{Wt. } U^{235} = \frac{A_{U5}}{A_{UO_2}} \left(\frac{N_{U5}}{N_{UO_2}}\right) \text{Wt. } UO_2 = \frac{235}{270}(0.1667)\, 489$$

$$= 71 \text{ lb} = 32.2 \text{ kg.}$$

The specific power of the reactor is

$$SP = \frac{488{,}000}{32.2} = 1515 \text{ kw/kg } U^{235}$$

The power density is

$$PD = \frac{488{,}000}{\overline{V_m}} = \frac{488{,}000}{4.78(6)} = 17{,}000 \text{ kw/ft}^3$$

$$= 601 \text{ kw/l}$$

It was assumed that the fuel loading would be varied radially throughout the core such that the reactor would have an approximately flat radial flux. The average flux in the reactor is

$$\bar{\phi} = \frac{P_C}{V_R\, \mathcal{E}_f}$$

$$N_{UO_2} = N_{x,UO_2}\left(\frac{V_{UO_2}}{V_R}\right) = \frac{2.445 \times 10^{22}}{(26.35)(3.25)^2}$$

$$= 8.80 \times 10^{15} \text{ molecules/cm}^3 \text{ reactor}$$

$$N_{U5} = \frac{N_{UO_2}}{\left(1 + \frac{N_{U8}}{N_{U5}}\right)} = \frac{8.80 \times 10^{19}}{6} = 1.468 \times 10^{19} \text{ atoms/cm}^3 \text{ of reactor}$$

$$\bar{\phi} = \frac{(488{,}000{,}000)(3 \times 10^{10})}{5.79\,(99)^3(352)(0.866)(1.468)\,10^{19}}$$

$$= 5.83 \times 10^{14} \text{ n/cm}^2\text{/sec}$$

It was assumed a graphite reflector two diffusion lengths thick would be suitable. The approximate reflector savings are as follows:

$$\delta \cong \frac{\lambda_{tr,core}}{\lambda_{tr,r}} L_r$$

$$\frac{\Sigma_{tr,core}}{N_{UO_2}} = \left[\frac{2.47}{e_v} + \frac{N_{BeO}}{N_{U5}}\left(\frac{9.10}{1 + \frac{N_{U8}}{N_{U5}}}\right) + 5.01\right] 10^{-24}$$

$$= 5.938 \times 10^{-21} \text{ cm}^{-1}$$

$$N_{UO_2} = 8.80 \times 10^{19}$$

$$\Sigma_{tr,core} = 0.524 \text{ cm}^{-1}$$

$$\lambda_{tr,core} = 1.91 \text{ cm}$$

$$\lambda_{tr,r} = 2.71 \text{ cm}$$

$L_r = 50\text{ cm}$

$\delta = \frac{1.91}{2.71}(50) = 35.2\text{ cm}$

$= 1.15\text{ ft}$

The reflector savings reduce the enrichment required.

The method of Fleck (101) was used to estimate the number of delayed neutrons which would be released in the reactor core:

$$M = \frac{(Ya/\pi g)^2}{1+(Ya/g)^2} + \frac{1}{2}\,\frac{\left[1+e^{-Yl/g}\right]\left[1-e^{-Ya/g}\right]}{\left[1-e^{-Y(a+l)/g}\right]\left[1+(Ya/\pi g)^2\right]}$$

M = probability that a neutron will be emitted in the core

a = core length = 6 ft

g = circulation velocity $\cong$ 50 fps

l = length of loop external to core $\cong$ 30 ft

Y = emitter decay constant = 0.08 for U^{235}

Substitution of these values into the equation gave:

M = 0.157

Thus, only 15.7 per cent of the delayed neutron will aid in reactor control.

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